

**OPTIMIZATION OF WATER-JET PROPULSION SYSTEM  
FOR SURFACE EFFECT SHIPS**

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FOR SURFACE EFFECT SHIPS

by

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ABSTRACT

Water-jet propulsion systems using flush inlet suitable for use on surface effect ships are studied. The equations governing the performance of the system are developed and incorporated into a computer program which optimizes the system on a least total weight basis. Resistance, displacement, range, speed, and other data are supplied to the program which then calculates total propulsion system weight for a number of jet velocity ratios. The system utilizes marine gas turbine engines coupled to multi-stage axial-flow pumps through planetary reduction gears. Variable area flush inlets and constant area nozzles are used. Results for a 2000 ton vessel are presented and show the influence of the jet velocity ratio on the weight and power requirements of the vessel. A FORTRAN computer program listing is included.

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# SYMBOLS USED IN TEXT

$A_j$	- Jet area	ft <sup>2</sup>
$A_p$	- Pump inlet area	ft <sup>2</sup>
$C$	- Ratio of entering water's momentum velocity to ship's velocity $V_m/V_o$	
$C_A$	- Acceleration coefficient	
$C_b$	- Pump blockage coefficient	
$C_D$	- Inlet drag coefficient	
$C_L$	- Pump length coefficient pump length over pump inlet diameter	
$C_w$	- Weight coefficient used for both inlet and pump	
$D$	- Inlet system drag	lb
$g$	- Acceleration due to gravity	ft/sec <sup>2</sup>
$h$	- Difference in height between outside waterline and diffuser exit	ft
$H_a$	- Atmospheric pressure head	ft
$h_e$	- Height of diffuser exit above inlet	ft
$h_{lep}$	- Head loss between diffuser exit and pump inlet	ft
$h_p$	- Height of pump above inlet	ft
$H_p$	- Change of head across pump	ft
$H_{p1}$	- Head at entrance to pump	ft
$h_{p2}$	- Head at pump exit	.
$H_2$	- Heat at diffuser exit	ft
$H_{sv}$	- Net positive suction head	ft



$HP_p$	- Horsepower delivered to the water	horsepower
$K$	- K-factor of reduction gear	
$L_p$	- Length of pump	ft
$r_g$	- Reduction gear ratio	
$n_p$	- Reduction gear input pinion RPM (ie engine RPM)	RPM
$N_s$	- Suction specific speed	$\frac{RPM(gal/min)^{.5}}{ft^{.75}}$
$p_v$	- Vapor pressure of water	ft
$PC$	- Propulsive coefficient	
$Q$	- Flow rate	$ft^3/sec$
	- Reduction gear Q-factor	
$R$	- Ship's resistance	lb
$r_h$	- Pump hub radius	ft
$r_h/r_t$	- Ratio of pump hub radius to blade tip radius	
$r_t$	- Pump blade tip radius	ft
$RPM$	- Pump or engine RPM	RPM
$SFC$	- Specific fuel consumption	lb/HP-hr.
$SHP$	- Required engine power output	horsepower
$T$	- Thrust	lb
$t$	- Time interval	hr
$U_t$	- Blade tip velocity	ft/sec
$V_j$	- Jet velocity	ft/sec
$V_j/V_o$	- Jet velocity ratio	
$V_m$	- Momentum velocity of entering water	ft/sec
$V_o$	- Ship's speed	ft/sec



$V_z$	- Velocity of water entering pump	ft/sec
$W_d$	- Pump weight	
$W$	- Weight of inlet system	lb
$W_g$	- Reduction gear weight	lb
$W_w$	- Weight of water in pump	lb
	- Density of water	$\frac{\text{slug/ft}^3}{\text{sec}^2}$
$\phi$	- Pump flow coefficient	
$\psi$	- Pump head coefficient	
$\pi$	- Pi	
$\eta_g$	- Gear efficiency	
$\eta_n$	- Nozzle efficiency	
$\eta_{OA}$	- Inlet system overall internal efficiency	
$\eta_{OA}'$	- Inlet system overall internal efficiency (uncorrected for height)	
$\eta_p$	- Pump efficiency	





## 1. INTRODUCTION

Vessels wholly or partially supported by a cushion of air are described as "surface effect ships". Recently, this term has evolved through usage to the point where it is used when referring to rigid sidewall captured air bubble vehicles, while vessels with flexible sidewalls are termed "air cushion vehicles". The rigid sidewalls together with flexible end seals enclose the air cushion on the SES. Most of the vessel's weight is supported on this cushion with the air being supplied by lift fans. The general configuration of the SES may be seen in figure 1.

By lifting the vessel's hull partially out of the water on an air cushion the resistance of the vessel is greatly reduced and the craft can be operated at high speeds with reasonable power requirements. There is no one typical drag versus speed curve for surface effect ships as the resistance depends on many factors including length to beam ratio, cushion pressure, sidewall length, sidewall width, and the amount of the frontal area. The effect of varying the length to beam ratio can be seen in figure 2. In general, it can be said that surface effect ships have lower resistances than conventional vessels and in many cases they have lower resistances than hydrofoils. The high length to beam ratio SES has a lower drag over a wide range as shown in figure 2. Thus a high length to beam ratio SES might be used for vessels operating at speeds between 35 and 60 knots and lower length



to beam ratio ships would be used for operations above this.

One of the major problems with surface effect ships is their propulsion systems. Operating at speeds over about 60 knots eliminated the possible use of conventional propellers due to cavitation. Air propellers, although efficient, take up much deck space and present a personnel hazard. In addition, they are not very efficient at low speeds and their weight is high. Supercavitating propellers can be efficient but they are noisy, they vibrate, and their operation in a seaway is uncertain. Water-jet propulsion systems are not very efficient but relatively simple, reliable, and flexible. The pumps, gears, and engines may be placed higher in the ship eliminating the need to widen the sidewalls. Thus the vessel's drag can be kept low. In addition to their poor efficiency, the weight of the waterjet system is a drawback. The water in the system is a significant factor in this weight.

The subject of this paper is the water-jet propulsion system for surface effect ships. The emphasis is on the weight and efficiency of the system. The final objective of this thesis was to develop a computer program which would select the optimum system for a given SES. The selection procedure for the system is based on least total weight including the fuel required for a given endurance. Specifically, the study was done for the U. S. Navy's contemplated 2000 ton 80 knot SES but the resulting program may be used for a number of different vessels. Previous studies have been made on water-



jet systems for hydrofoils (see references 2,3, and 4) and much of the information contained in the previous studies was used for the pump and engine segments of the program. The concentration in this paper is on the flush inlet system which may be used for the surface effect ships and is not applicable to the hydrofoil.



## 2. SYSTEM DESCRIPTION

The water-jet propulsion system for a SES is made up of eight components: the inlet opening and associated fairing, a movable ramp, the diffuser, the pump, the reduction gear, the engine, the nozzle, and necessary piping, as shown in figure 3. The inlet is described as being flush since it lies in the same plane as the bottom of the hull. The primary concern here is to minimize drag while bringing the water into the hull. The curvature of the leading edge and the radius of the lip are important parameters in this respect. To prevent separation of the flow the leading edge curvature must not be too sharp. At the same time, too shallow a bend results in heavier systems. The lip radius should be made as small as possible to minimize drag but is constrained by several factors. Cavitation prevention, debris damage resistance, and the possible need to place sensors near the lip put lower limits on the lip size. The inlet ratio (the ratio of the inlet width to inlet height) also effects drag. With low aspect ratios having lower drag. At the same time, the smaller aspect ratio inlets may require longer and heavier transition sections after the diffuser.

The movable ramp opens the inlet at low speeds to allow more flow through the system. The variation of area depends on the drag characteristics of the vessel, the operating speed, the jet velocity ratio, and other factors. In the 2000 ton vessel example, the power requirements at hump speed and at





cruise are nearly the same, and the required flow rate of water is nearly the same. Thus, the ratio of the inlet area at hump to area at cruise should be about equal to the ratio of the ship's velocity at cruise to the velocity at hump.

The diffuser, downstream of the flush inlet, slows the flow down to prevent cavitation at the pump. Diffuser design is crucial to the system. On one hand a shallow diffuser angle is desired to minimize losses and on the other a shallow angle increases the diffuser length and consequently the weight of the system. Appendix A gives data for the diffuser used in the study. Additional information on the inlet, diffuser, and other design aspects of the system can be found in reference 1.

The pump used in the study consists of an inducer stage followed by one or more axial stages. The flow coefficient of the inducer stage was set at 0.15 to give diffuser ratios similar to those for which data was available in reference 1. It was further assumed that there would be one engine per pump and that all engines and pumps would be identical. Since it was assumed that each engine would drive a single pump and because of their light weight, planetary reduction gears would be used. Further details of pumps, gears, and engines will be presented in chapter 4.

The nozzles and additional piping of the system is not considered in detail in the program. Provision for their weights is made but other than allowing for an assumed nozzle



efficiency and the difference in height between the diffuser outlet and the pump, the head losses are ignored as being small compared to the remainder of the system.



### 3. DEVELOPMENT OF EQUATIONS

A waterjet propulsion system produces thrust by increasing the momentum of the ingested water. Thus the thrust developed is given by:

$$T = \rho Q (V_j - V_m) \quad (3.1)$$

or, defining  $C = V_m/V_o$

$$T = \rho Q (V_j/V_o - C) V_o \quad (3.2)$$

In steady state the thrust must equal the total resistance of the ship which is the resistance of the hull plus the drag caused by the propulsion system. Or,

$$T = R + D \quad (3.3)$$

Reference 1 gives the drag of the inlet system in terms of a drag coefficient,  $C_D$ . Thus,

$$D = C_D Q V_o \ell / 2 \quad (3.4)$$

Figure 4 shows the drag coefficient versus speed curves for varying aspect ratio inlets.

Combining 3.2, 3.3, and 3.4 yields

$$\rho Q (V_j/V_o - C) V_o = R + C_D Q V_o \ell / 2 \quad (3.5)$$

When the vessel is accelerating (such as over the hump region) the thrust must be greater than the total resistance. Or, letting  $C_A$  be the acceleration coefficient, 3.5 becomes:

$$\rho Q (V_j/V_o - C) V_o = C_A (R + C_D Q V_o \ell / 2) \quad (3.6)$$



Where  $C_A > 1$ . Equation 3.6 can then be solved for  $Q$ .

$$Q = C_A R / \rho V_o (V_j/V_o - C - C_A C_D/2) \quad (3.7)$$

Since the power delivered to the water is given by:

$$HP_p = H_p Q \rho g / 550 \quad (3.8)$$

and  $Q$  is given by equation 3.7, only an expression for  $H_p$ , the head across the pump is needed.

Reference 1 defines the overall internal efficiency of the system ( $\eta_{OA}$ ) as a measure of the head recovery between the inlet and the diffuser outlet. Figures 5 and 6 show  $\eta_{OA}$  versus vessel speed for the varying aspect ratio inlets. These curves are  $\eta_{OA}$  for infinite Froude number or diffusers whose exits lie in the same plane as their inlets. In the actual case, these efficiencies must be corrected for the change in elevation between inlet and outlet. The corrected efficiency is:

$$\eta_{OA} = \eta_{OA'} - h/v_m^2/2g. \quad (3.9)$$

Therefore, the total head at the diffuser outlet is:

$$H_2 = \eta_{OA} v_m^2/2g \quad (3.10)$$

and the head at the entrance to the pump is:

$$H_{p1} = h_p - h_e + H_2 - h_{lep} \quad (3.11)$$

Assuming that the nozzle is at the same elevation as the pump and ignoring the nozzle efficiency, the head at the





exit of the pump is:

$$H_{p2} = v_j^2 / 2g \quad (3.12)$$

Equations 3.10, 3.11, and 3.12 can be combined to get the head rise across the pump.

$$H_p = v_j^2 / 2g - \eta_{OA} v_m^2 / 2g + h_p - h_e + h_{lep} \quad (3.13)$$

Making the assumption that  $h_{lep}$  (the loss between the diffuser outlet and the pump entrance) is small compared to the other terms and letting  $h_p - h_e$  be  $h$ , 3.13 becomes:

$$H_p = ((v_j/v_o)^2 - c^2 \eta_{OA}) v_o^2 / 2g + h \quad (3.14)$$

and substituting 3.7 and 3.14 into 3.8 gives

$$HP_p = \frac{C_A R v_o ((v_j/v_o)^2 - c^2 \eta_{OA} + 2hg/v_o^2)}{(550) (2) (v_j/v_o - c - C_A C_D/2)} \quad (3.15)$$

The shaft horsepower required is then:

$$SHP = HP_p / \eta_p \eta_g \eta_n \quad (3.16)$$

The propulsive coefficient is defined as the thrust divided by the shaft horsepower. Incorporating the gear and nozzle efficiencies into the pump efficiency PC becomes:

$$PC = \frac{2 v_p (v_j/v_o - c - C_A C_D/2 + C_A C_D / (2v_o))}{((v_j/v_o)^2 - c^2 \eta_{OA} + 2hg/v_o^2)} \quad (3.17)$$

By taking the derivatives of 3.15 and 3.17 with respect to



$V_j/V_o$  and setting the results equal to zero expressions can be found for the velocity ratios for which the required horsepower is minimum and the propulsive coefficient is maximum. These are :

$$V_j/V_o = C + C_A C_D / 2 + (C + C_A C_D / 2)^2 - C^2 \eta_{OA} + 2hg/V_o^2 \quad (3.18)$$

for minimum power and

$$V_j/V_o = C + C_A C_D / 2 - C_A C_D / 2V_o + (C + C_A C_D / 2 - C_A C_D / 2V_o)^2 - C^2 \eta_{OA} + 2hg/V_o^2 \quad (3.19)$$

for maximum PC. Because of the definition of PC the minimum power does not occur at the maximum PC. The two velocity ratios are close enough, however, that either can be used in connection with equation 3.15 to estimate the power required by the SES.

As shown below, the problem is not as simple as just using these equations to predict requirements. Once a jet velocity ratio at cruise is selected from equation 3.18 or 3.19 the flow rate through the system is determined from equation 3.7 and the area of the jet is:

$$A_j = Q/(V_o(V_j/V_o)) \quad (3.20)$$

Then using a constant area jet, Q equals the jet area times



the jet velocity and equation 3.6 can be used to solve for the jet velocity ratio at hump.

$$(V_j/V_o)_{\text{Hump}} = .5C + C_A C_D/4 + \frac{(.5C + C_A C_D/4)^2 + C_A R / (\rho A_j V_o^2)}{(3.21)}$$

Where all terms are at the hump speed. The jet velocity ratio is then used to determine the flow rate, head rise across the pump and the horsepower required by use of equations 3.7, 3.8, and 3.15 respectively. The use of a constant area jet links the two velocity ratios together and it is possible that by using the power optimum jet velocity ratio at cruise will result in a velocity ratio at hump which is far from the power optimum at hump. In fact, with a given set of conditions there may be no possible jet velocity ratio, at which the ship is both able to accelerate over the hump and able to cruise at the desired speed. In this case, either the cruise speed or the acceleration margin would have to be reduced or larger or more engines would have to be used. Appendix B presents a sample calculation using the above equations and figure 12 shows the variation of propulsion coefficient with jet velocity ratio and the range of velocity ratios which may be used for this example.

The weight of the inlet system including the water up to the diffuser outlet is given in reference 1 as:



$$W = C_w Q^{1.5} \quad (3.22)$$

Values of  $C_w$  versus speed are shown in figure 7 for the varying aspect ratio inlets. The weight given by equation 3.22 represents the total weight of the system including structure, ducting, and water. Additional ducting such as the transition pipe, pump elbow, and nozzle pipe are not included. As can be seen from equation 3.7 the flow rate decreases with increasing jet velocity ratio. Thus the weight of the inlet system will decrease with increasing velocity ratio. Since the propulsive coefficient versus velocity ratio curve is relatively flat for high velocity ratios it should be anticipated that the lightest system will have a high jet velocity ratio.

As was mentioned previously, the aspect ratio is the ratio of the inlet width to the inlet height. As used here the term "varying aspect ratio" inlets means those with aspect ratios equal to the system's diffusion ratio. Other inlets are termed "fixed aspect ratio" inlets. The varying aspect ratio inlets in general are more efficient and lighter. The movable ramp is greatly simplified by using diffusion ratios equal to the inlet aspect ratios. The area is varied by moving the roof of the inlet. Thus, in general it is desirable to use the varying aspect ratio inlets. In some cases, this will not be possible due to sidehull width constraints. That is, using an aspect ratio equal to the diffusion ratio could result in an inlet width which would be





as wide or wider than the hull. In these cases smaller aspect ratios must be used. Reference 1 presents data on 2.5 aspect ratio inlets and it is repeated in figures 8, 9, 10, and 11.



## 4. PUMPS, REDUCTION GEARS AND ENGINES

### 4.1 PUMPS

The pumps considered for use in SES water-jet propulsion systems are centrifugal and axial flow pumps. Since the available data on the inlet system is for systems of 10,000 to 40,000 horsepower and the head rise, flow rate, and suction specific speeds required in the system are all high, it appears that axial flow pumps are better suited for this application. Previous comparisons of axial flow and centrifugal pumps in water-jet systems (ref. 2) having nearly the same requirements show that the centrifugal pumps are usually much heavier and their placement in the system is much more complicated. Generally multi-parallel stages are required and the associated gearing, shafting, and ducting is complicated and heavy. Centrifugal pumps are, therefore, not considered in this paper.

Two factors affected the choice of axial flow pumps used in this system. First, the data presented in reference 1 was based on a specific pump. This was a pump whose inlet flow coefficient is 0.15 and could operate at suction specific speeds of up to 16,000. Because the system's diffusion ratio depends on the pump flow coefficient and the inlet system data was presented for specific diffusion ratios; the use of 0.15 for the flow coefficient was dictated. The suction specific speed is the second factor. Although pumps have been built and operated at suction specific speeds as high as



26,000 it was decided to limit the pumps in this system to 16,000, as being more reasonable. The pump assumed in the calculation procedure is constrained to operate below a specific speed of 16,000.

The above limit does not guarantee that the pump will be cavitation free at hump speeds. Reference 5 presents data on a pump operated up to a suction specific speed of 26,000. It points out that although the pump had good performance characteristics up to this speed, cavitation was present at about a suction specific speed of about 3,800. Cavitation normally occurs first on the inducer stage. In general, however, the inducer still produces enough head rise to keep the remaining stages from cavitating. Thus, when more than one stage is used the performance of the pump is not greatly effected by cavitation on the inducer stage. It is therefore indicated that the pump may very well cavitate while the vessel is accelerating, but that there should be no major loss in performance.

Besides loss of pump performance in a cavitating regime possible pump damage must be considered. This damage depends both on the extent of cavitation and on the length of time the pump is operated in this condition. More extensive test data on pump deterioration is desirable. A study on the dynamics of a surface effect ship using a water-jet propulsion system was undertaken by Bruce (reference 6) and shows the acceleration characteristics of the vessel. Although his results



show a long acceleration period before the vessel reached cruise speed (about 4 minutes), the period of time spent in the hump region is quite short (about .5 minutes). This suggests that some cavitation can be tolerated.

Using high suction specific speeds leads to high pump speeds (RPM). Consequently, small reduction ratios are needed and weight is saved in the reduction gears. The RPM is limited indirectly by the maximum allowable blade tip speed. In this instance, the maximum tip speed is limited to 200 feet per second.

The head coefficients for the pump were set at 0.41 for the inducer and 0.3 for the following stages. In an actual pump design, the inlet flow coefficient and the head coefficients cannot be simply arbitrarily selected. Pumps have been built which have coefficients approximately equal to these so they are considered reasonable even though they may not be the optimum for all designs. Since the methods of estimating the weight of pumps do not correspond very well to weights of produced pumps, using slightly different coefficients to estimate the pump size should induce very little additional error in the total system weight. Users of this program should be cautioned to ensure that their particular pump requirements are reasonably satisfied by the pump design used here.

Knowing the flow rate and head rise through the pump from equations 3.7 and 3.13 the pump design proceeds as follows. The flow coefficient relates the axial velocity





of the entering water to the blade tip velocity.

$$\phi = V_z/U_t \quad (4.1.1)$$

and the head rise coefficient relates the head rise across the pump to the blade tip velocity.

$$\Psi = gH_p/U_t^2 \quad (4.1.2)$$

using equation 4.1.1 with  $\phi = .15$  and  $U_t$  equal to its maximum permissible value of 200 ft/sec,  $V_z$  is found and then  $r_t$  is found by:

$$r_t = Q/V_z \pi (1 - (r_h/r_t)^2)^2 \quad (4.1.3)$$

Since the inlet area of the pump is  $\pi(r_t^2 - r_h^2)$ . Knowing  $r_t$  and  $U_t$  sets the pump RPM ( $\text{RPM} = 30 U_t/\pi r_t$ ). The suction specific speed is then calculated by:

$$N_s = \text{RPM } Q^{.5}/H_{sv}^{.75} \quad (4.1.4)$$

Where  $Q$  is in gallons/minute and  $H_{sv}$  is the net positive suction head

$$H_{sv} = H_a + H_{p1} - p_v \quad (4.1.5)$$

If  $N_s$  exceeds 16,000 the tip velocity is reduced and  $r_t$ , RPM, and  $N_s$  are recalculated until  $N_s$  is equal to or less than 16,000.

The efficiency of the pump at the design speed is assumed to be 91.5% for a pump whose diameter is 3.66 feet. This is the same at what is used in reference 2. As in reference 2,



a Reynolds Number correction is applied for the actual pump diameter to determine the pump efficiency. This efficiency is then used to find the propulsive coefficient at hump speed and the required shaft horsepower is calculated and compared to the available SHP. If the required SHP is less than or equal to the available power the vessel will be able to accelerate over the hump (the acceleration coefficient is included in the required power) and the design may be continued. If not, the pump blade tip speed can be reduced. This increases the pump diameter and, therefore, the efficiency. It also encreases the head coefficient of the pump according to equation 4.1.2. The number of stages is determined from the resulting head coefficient. That is, the inducer is allowed a head coefficient of 0.41 and each subsequent stage 0.30.

The off design point pump RPM and efficiency are found in the same manner as presented in references 2 and 3. That is, the pump head, efficiency and RPM characteristics are assumed parabolic. The coefficients used are the same as those in reference 2 and the characteristics for two or three stage pumps are assumed to be identical. After finding the efficiency and RPM at the cruise speed, the propulsion coefficient, required power and blade tip speed are found. The required power is compared to available power and the blade tip speed is checked against the 200 ft/sec limit. If either of the above are unacceptable, the blade tip speed at the hump speed is decreased and the entire procedure is



repeated. The pump dry weight is calculated by the equation:

$$W_d = C_w D^{2.3} \quad (4.1.6)$$

and the weight of the water in the pump by:

$$W_w = C_b A_p L_p \rho g \quad (4.1.7)$$

Where  $C_b$  is a blockage coefficient and  $L_p$ , the pump length is given by:

$$L_p = C_L D \quad (4.1.8)$$

In general, increasing the pump diameter or decreasing the blade tip speed increases the pump efficiency slightly and greatly increases the pump weight.



## 4.2 REDUCTION GEARS

It is assumed that planetary reduction gears will be used in these systems. Since the LM 2500 gas turbine which is being considered for use on the United States Navy's 2000 ton SES puts out a maximum of 22,500 shaft horsepower the gears must be capable of transmitting this. The feasibility of planetary gears of this size has been demonstrated by a 40,000 SHP gear built by Curtiss-Wright.

The weight of the reduction gear is estimated using the Dudley method. The weights obtained from this method correlate well with existing gears. Two factors (K and Q) are used in the method. An important portion of the tooth stress is proportional to the square root of the gear's K-factor. The range of K-factors which are reasonable for use on surface effect ships is between 400 and 800.

The second factor, Q, is defined as:

$$Q = HP (m_g + 1)^3 / n_p m_g \quad (4.2.1)$$

Where  $m_g$  is the reduction ratio,  $n_p$  is the speed of the input pinion in RPM and HP is the shaft horsepower. In effect, this definition relates the gear's required geometry to the weight. The resulting weight equation for planetary gears is:

$$W_g = 9500 Q/K \quad (4.2.2)$$

Figure 13 shows the weight correlation for a limited number of gears. The weights given by 4.2.2 include the gear, casing,





oil reservoir, oil pump, and stub shaft but not the oil or necessary foundation.



#### 4.3. ENGINES

Gas turbine engines designed for or modified for marine use may be employed in water-jet systems. Although high speed diesels may be used, in general they are heavier and have not been considered. This may not be a valid assumption in all circumstances when the total system is considered. Some gas turbines have very poor specific fuel consumptions and the added weight of required fuel may offset the engine weight saved by using the lighter weight turbine. The twelve engines used in references 2 and 3 are again used here with the same characteristics. That is, normal SHP, maximum SHP, specific fuel consumption, shaft RPM, and engine dry weight are inputs to the program. As in references 2 and 3 the specific fuel consumption is assumed to vary with the ratio of SHP to normal SHP raised to a power,  $n$ . The value of the power,  $n$ , changes when this power ratio is 0.7. Since the pump RPMs at cruise and hump speed are determined by the pump design as are the power requirements, it is assumed that the engine can develop the required power at the corresponding shaft speeds. No consideration of the engine's power versus RPM characteristics is made. These assumptions may not be valid for all engines or all operating ranges and once again the user is cautioned.

The fuel consumption is found by dividing the endurance time into steps. The fuel required for each step is:

$$W_f = (SFC) (SHP) (t) \quad (4.3.1)$$



When the weight for one time period is found, it is subtracted from the vessels weight and the resistance of the vessel is recalculated using a constant lift to drag ratio. The resistance of an actual SES will not vary in this way but will decrease as weight is removed (L/D will not be constant. Reference 7). To show some decrease in resistance and because of the fact that the weight of the fuel used by the lift fans is ignored in the program, the above assumption seems reasonable. Accounting accurately for the lift fan fuel and the decreasing resistance of the vessel would be possible but extremely complicated. On the other hand, since the fuel makes up a substantial amount of the total ship weight its expenditure is significant.

Since the jet area is fixed,  $Q = V_j A_j$  and equation 3 becomes:

$$A_j \rho (V_j^2 - V_m V_j) = R + C_D \rho A_j V_j V_o / 2 \quad (4.3.2)$$

and can be solved for  $V_j$ .  $R$  is the new resistance after the fuel is removed. Then assuming the pump efficiency remains constant, the shaft horsepower required is:

$$SHP = \frac{g A_j V_j (V_j^2 / 2g - V_m^2 \eta_{OA} / 2g - h)}{550 \eta_p \eta_g \eta_n} \quad (4.3.3)$$

The fuel required for the next time interval is calculated using this horsepower.



## 5. RESULTS

Table 1 is output from the computer program for the 2000 ton 80 knot test case and for jet velocity ratio equal to 1.9463. Table 2 shows a summary of data for the same vessel and a variety of jet velocity ratios.

In the weight summary it should be noted that the inlet system and the fuel (1000 mile range) make up 86.7% of the total system weight. In addition, the inlet system's drag makes up about 7% of the total resistance. In this run the pumps were assumed to be at the same height as the diffuser outlet and, therefore, the additional water weight is zero. Based on the assumptions in chapter 4, the transition pipe would add about 3,130 pounds of water for each foot which the pump is elevated above the diffuser outlet. Therefore, even a 10 foot difference would have little effect on the total weight. Since the engine (LM2500) used in this case has an excellent specific fuel consumption (.41 at normal horsepower), the fuel weight represents a minimum weight. It is doubtful that any significant saving in weight could be made by using high speed diesel engines or any other turbine.

The pump flow rates at cruise and hump speeds are nearly identical as are the pump heads. This results in nearly equal efficiencies at the two conditions. The pump runs only about 40 RPM slower at cruise speed than at hump speed and because of the high pump speed (about 1200 RPM) a reduction gear ratio of only 2.79 is required. The resulting reduction





gear is lightweight. The required engine speed and horsepower changes between hump speed and cruise speed correspond well with the engine's performance characteristics.

The inlet data shows that the movable ramp must move about 1.72 feet to admit the necessary flow at hump speed. This seems reasonable. It should also be noted that the width of the inlet is 4.17 feet. This should cause no problems in the design of the sidehulls. The required diffusion ratio is 4.0164 and the data used in the program was based on a diffusion ratio of 4 for an 80 knot ship.

The summary of data for various jet velocity ratios (table 2) dramatizes the affect which the velocity ratio has on the weight ratio, propulsive coefficient, and power requirements. The maximum propulsive coefficient occurs at velocity ratio equal to 1.8263 as does minimum cruise horsepower. According to equation 3.19 the propulsive coefficient should be maximum at jet velocity ratio equal to 1.8063. In the developement of equation 3.19 it was assumed that the pump efficiency is independent of jet velocity ratio. In the program the pump efficiency is dependent on the velocity ratio and as a result the maximum propulsive coefficient occurs at a higher velocity ratio.



## 6. CONCLUSIONS AND RECOMMENDATIONS

The high weight of the water-jet propulsion system is a drawback to its use. The water in the system and the required fuel make up the largest portion of the weight. As can be seen from the results presented previously, using a higher jet velocity ratio reduces the weight of the system without seriously affecting the overall propulsive coefficient. In most cases it appears that to obtain the least weight system the velocity ratio should be set at its highest possible value. This limit occurs when the power required to accelerate or cruise exceeds the available power.

The low efficiency of the system contributes to the high weight of fuel. Only about 7% of the total drag of the vessel is due to the inlet system. Although it may be possible to reduce this through the use of a better design, little saving of weight would be achieved. An increase in the overall internal efficiency of the diffuser will result in a lighter system. However, a 10% increase in the internal efficiency will result in less than a 1% increase in the propulsive coefficient and thus reduce the system's weight.

In summary, it appears that although some improvements may be made in the flush inlet water-jet system, the saving in weight will be small. The drag of the inlet, the internal efficiency of the diffuser, and the pump efficiency may be improved. The drag is already low and the efficiencies are high, so little improvement should be expected.



More experimental data on inlets and diffusers is needed. As is more data on axial flow pumps. This data should then be incorporated into the computer program. It is also recommended that the weight of the lift fans and their required fuel also be added to the program, along with a more accurate method of predicting the variation of drag as weight is removed. An arrangement feasibility study is also needed. The effects of splitting the flow between the pumps should be included in this.



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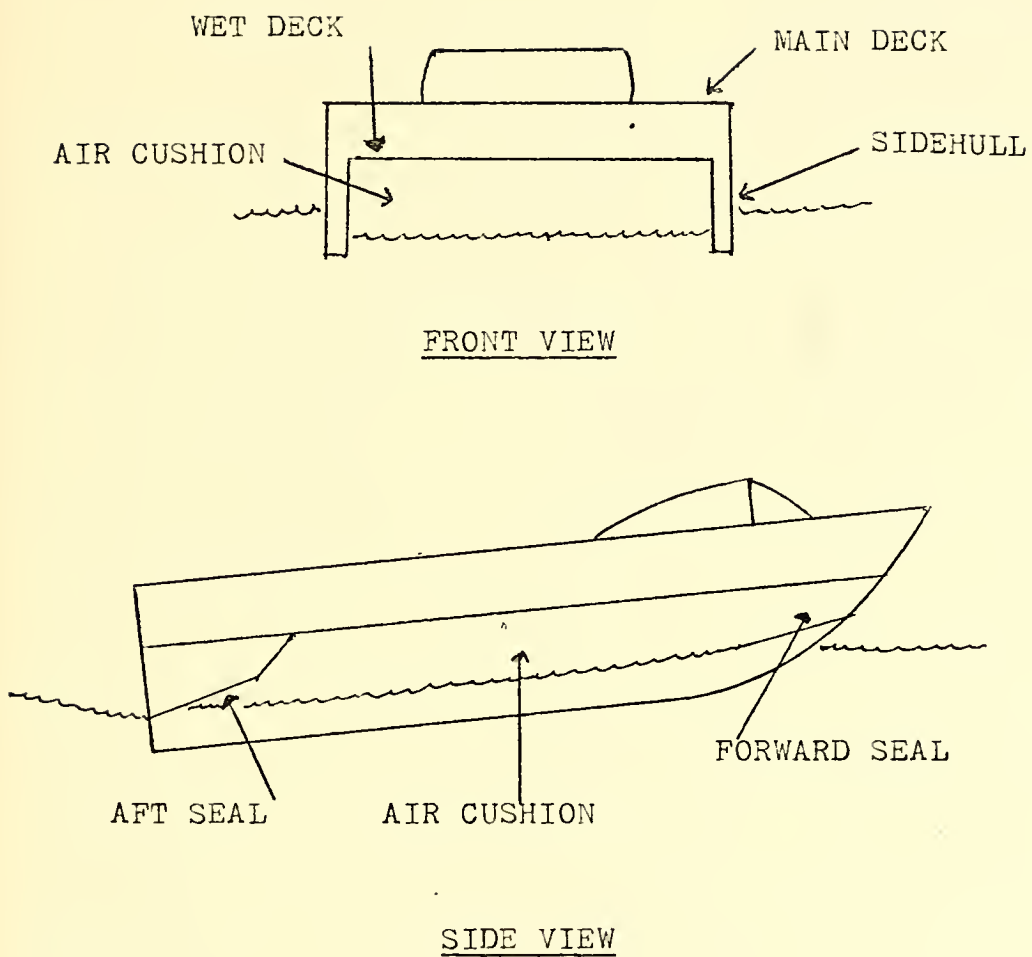


Figure 1 - GENERAL CONFIGURATION OF AN SES



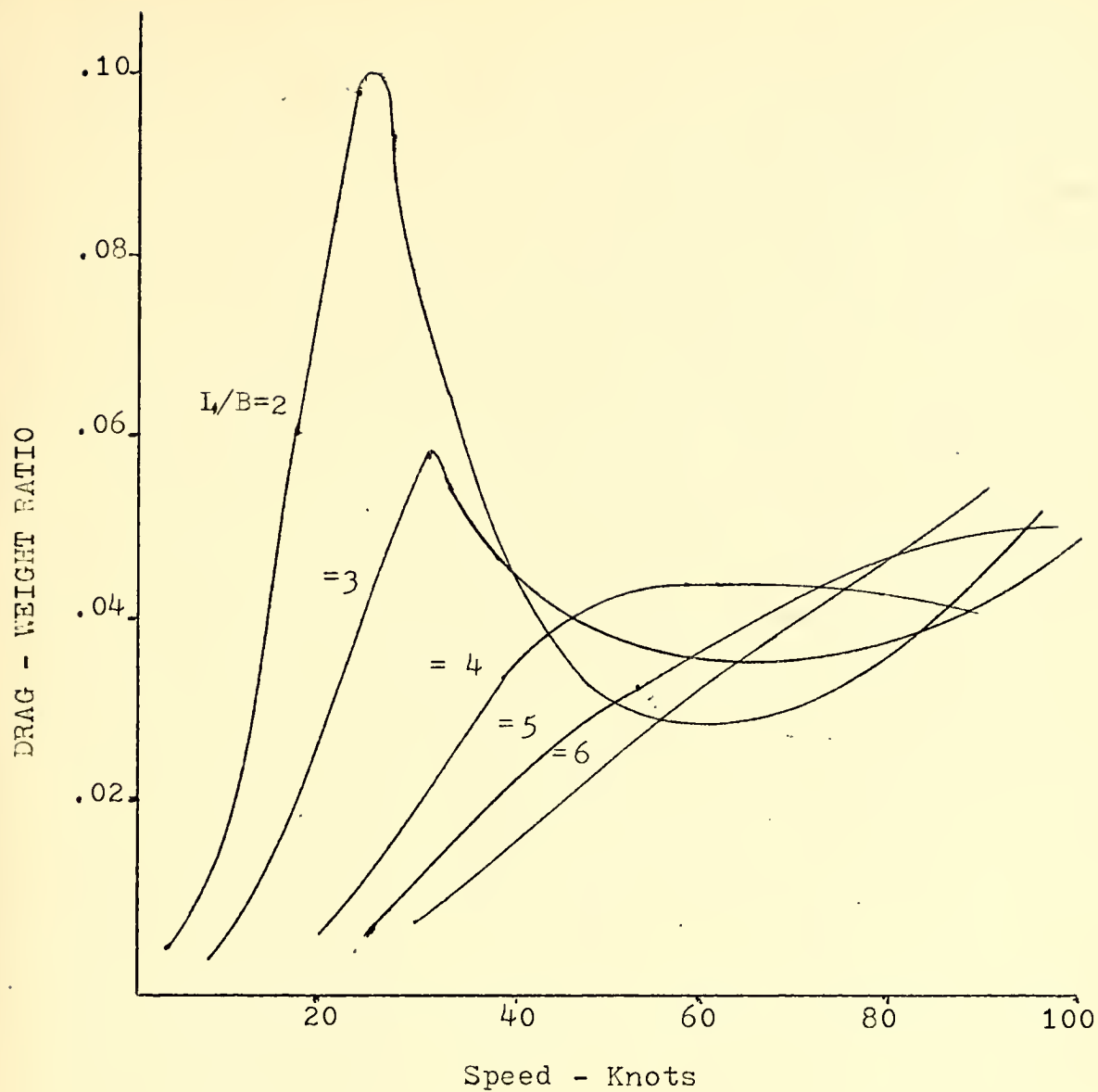


Figure 2 - VARIATION OF DRAG WITH VESSEL SPEED AND LIFT TO DRAG RATIO FOR SURFACE EFFECT SHIPS



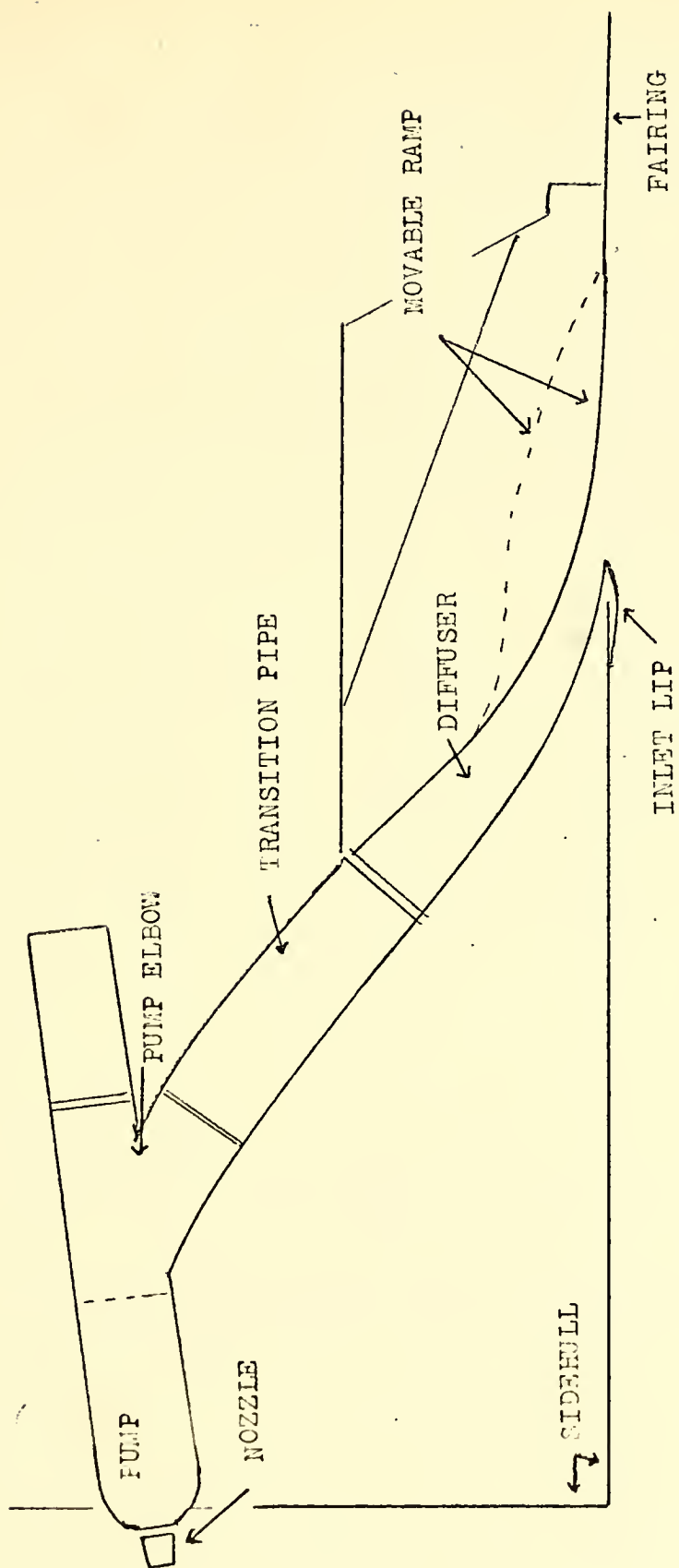


Figure 3 - PROPULSION SYSTEM ARRANGEMENT





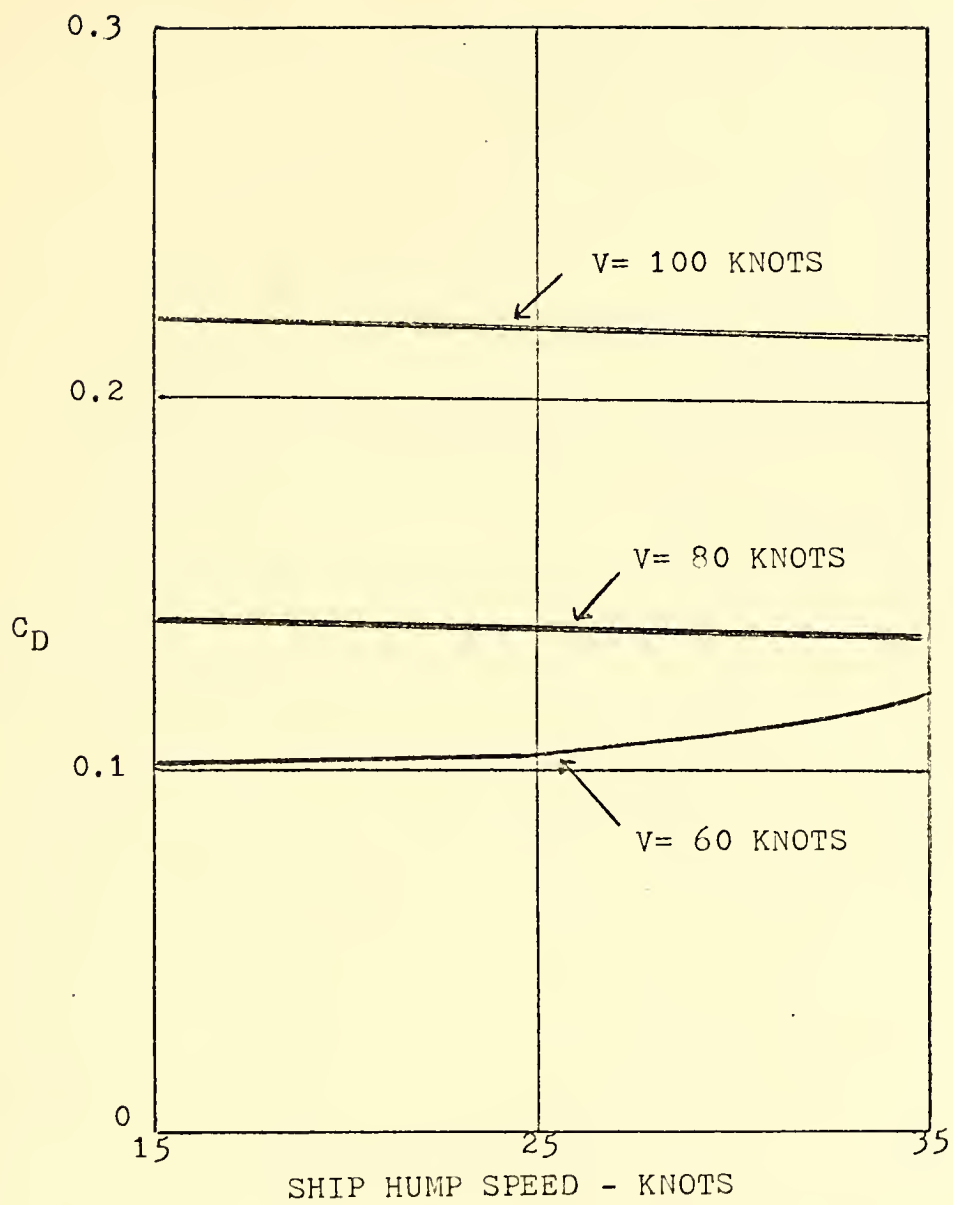


Figure 4 - INLET DRAG COEFFICIENT FOR VARYING APECT RATIO INLETS. (ref. 1)



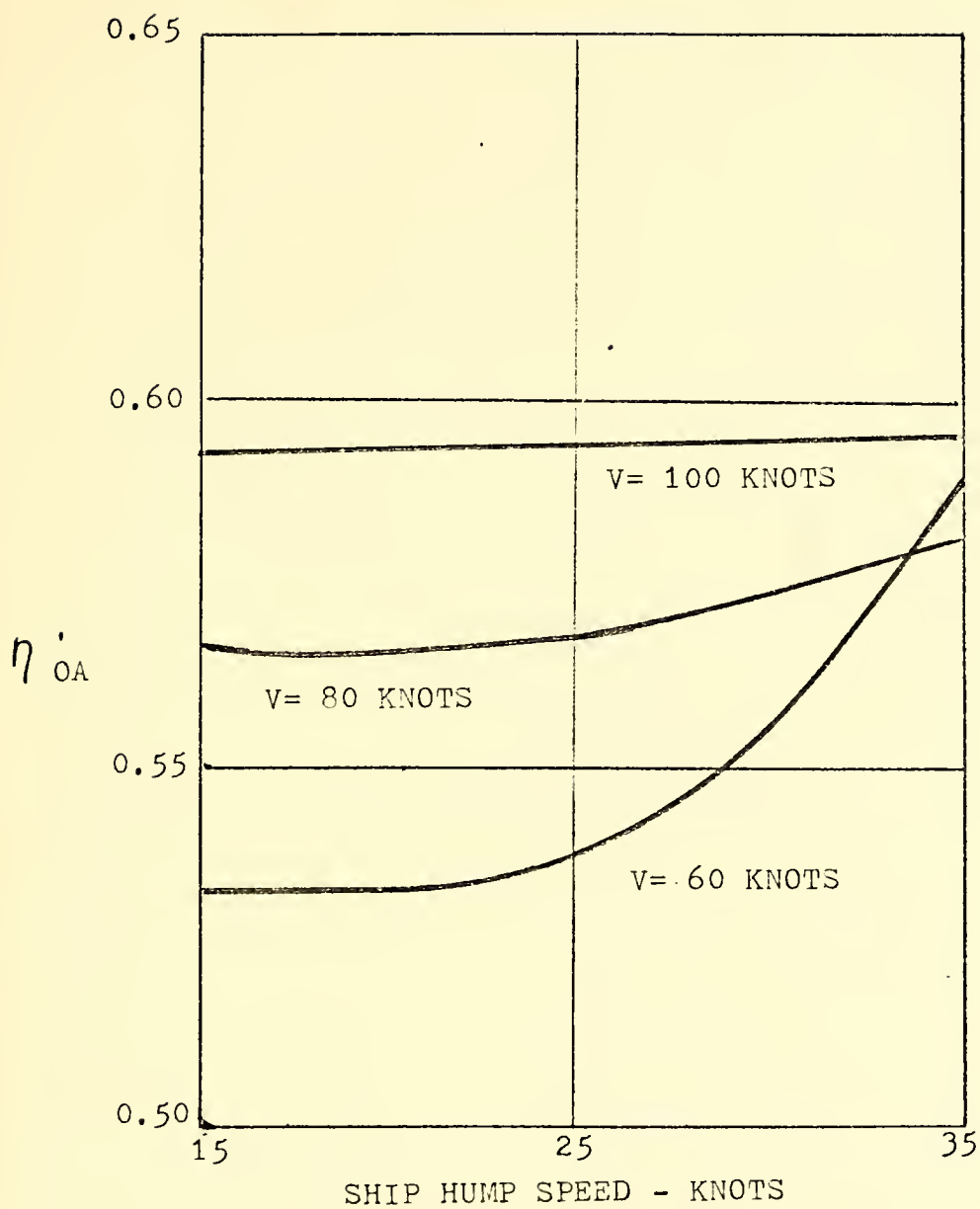


Figure 5 - DESIGN SPEED OVERALL INTERNAL EFFICIENCY  
FOR VARYING ASPECT RATIO INLETS



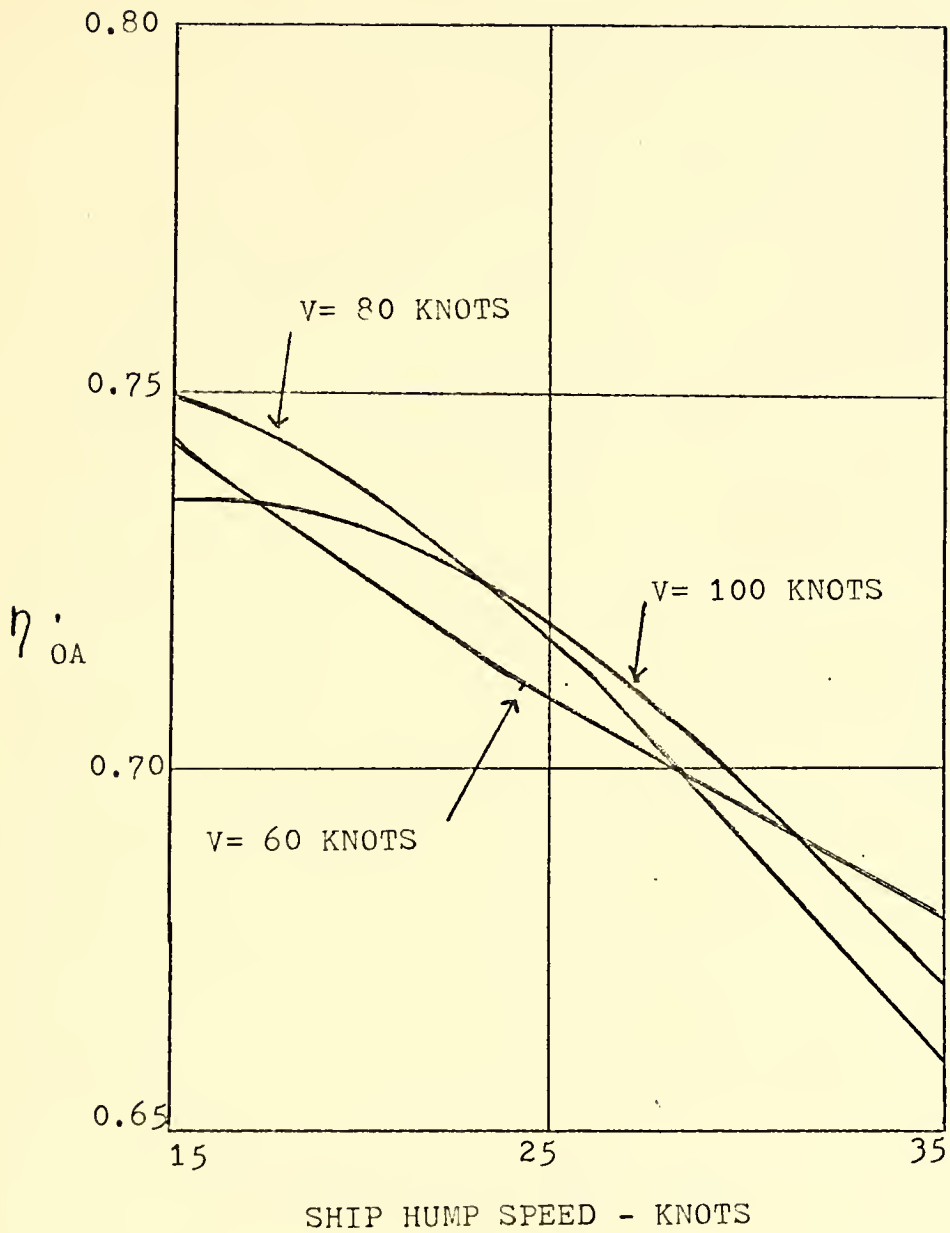


Figure 6 - HUMP SPEED OVERALL INTERNAL EFFICIENCY  
VARYING ASPECT RATIO INLETS



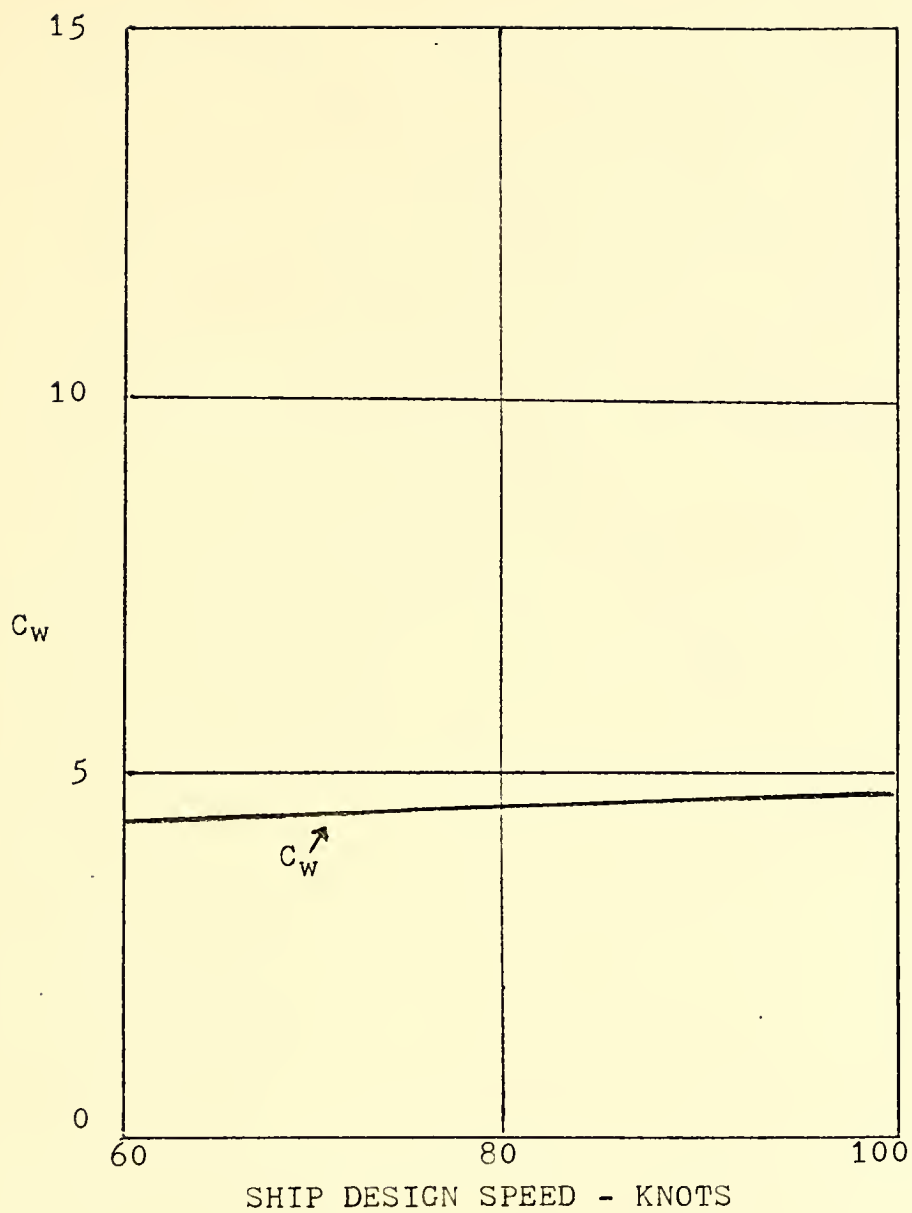


Figure 7 - TOTAL INLET SYSTEM WEIGHT COEFFICIENT FOR VARYING ASPECT RATIO INLETS





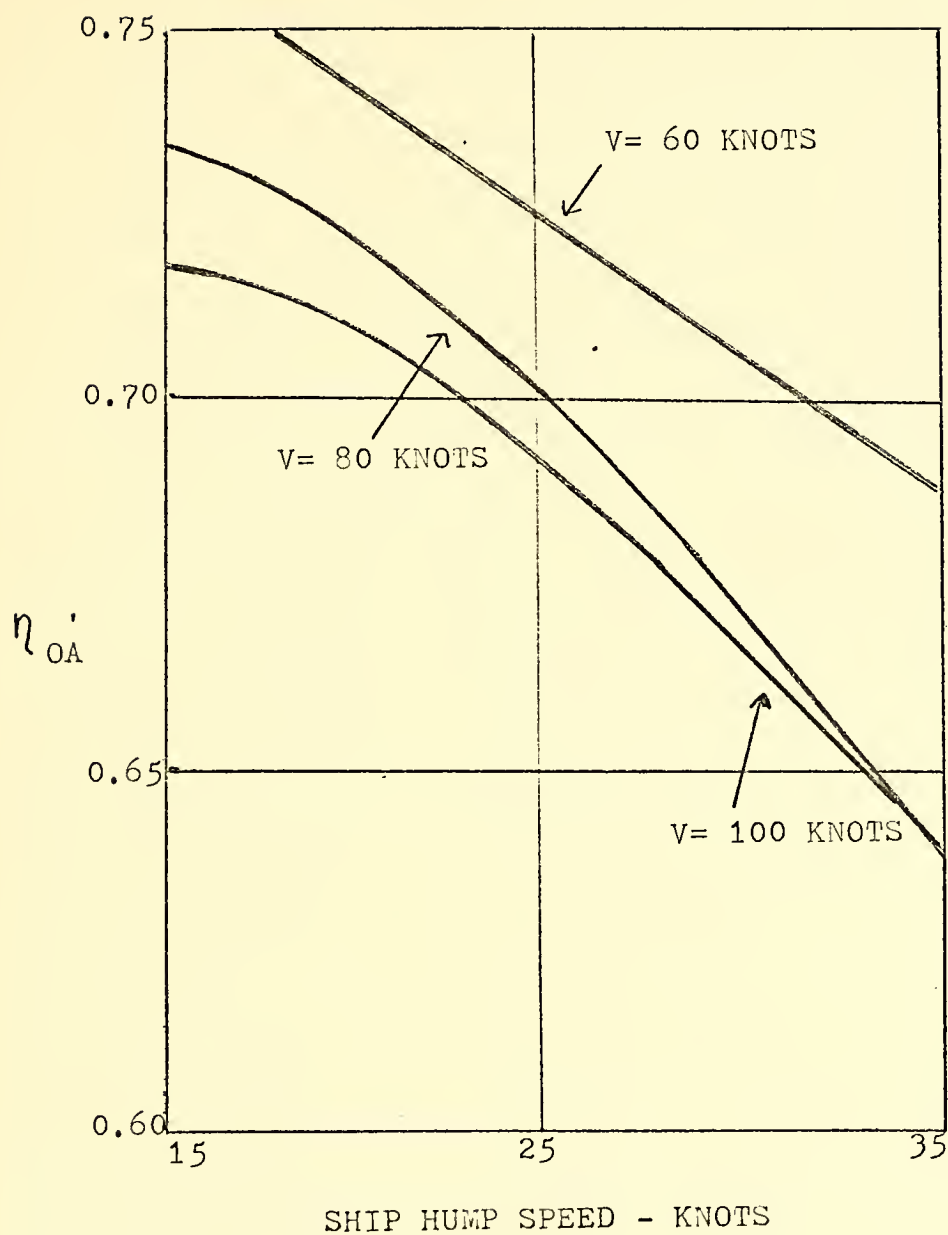


Figure 8 - HUMPS SPEED OVERALL INTERNAL EFFICIENCY  
FOR 2.5 ASPECT RATIO INLETS



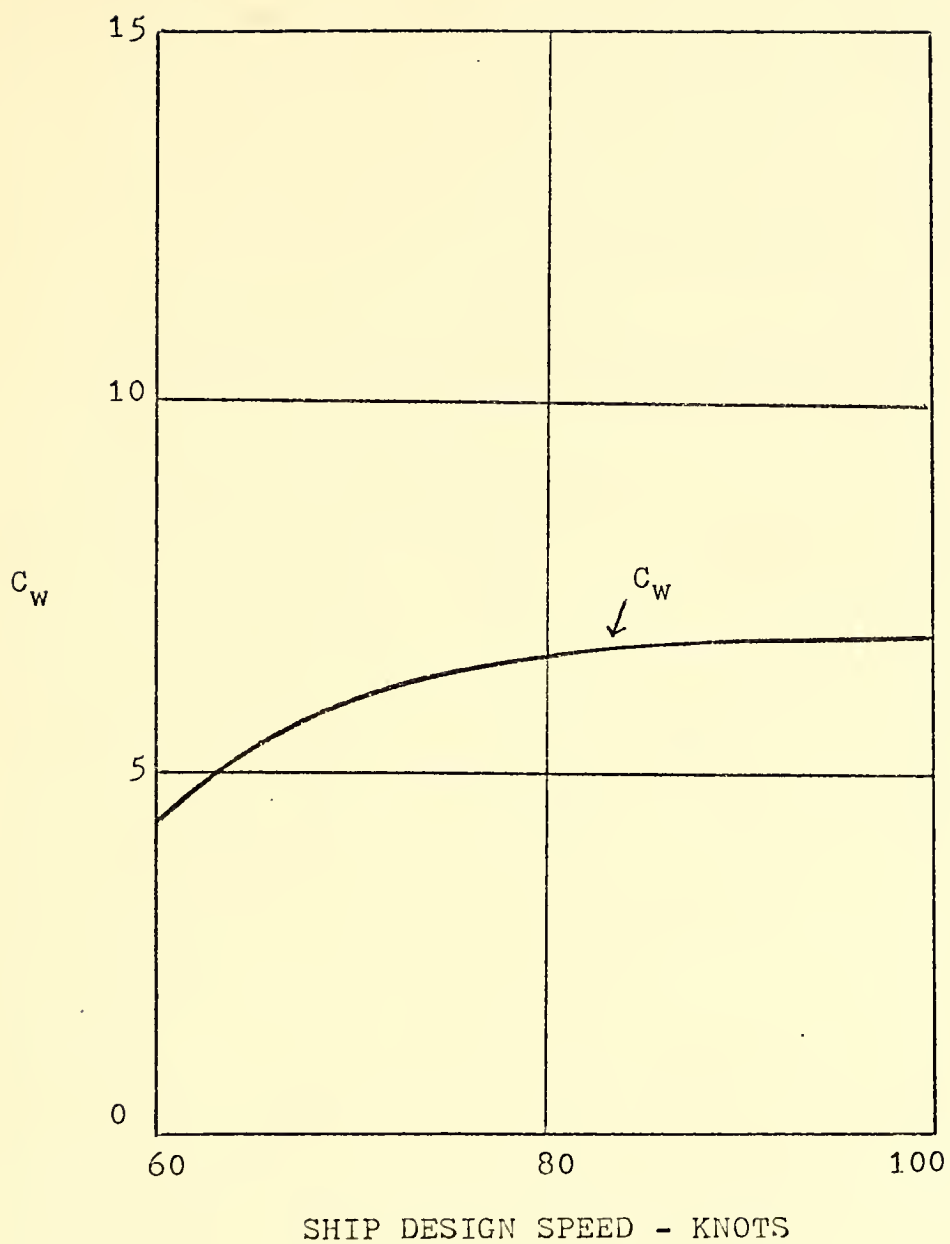


Figure 9 - TOTAL INLET SYSTEM WEIGHT COEFFICIENT  
FOR 2.5 ASPECT RATIO INLETS



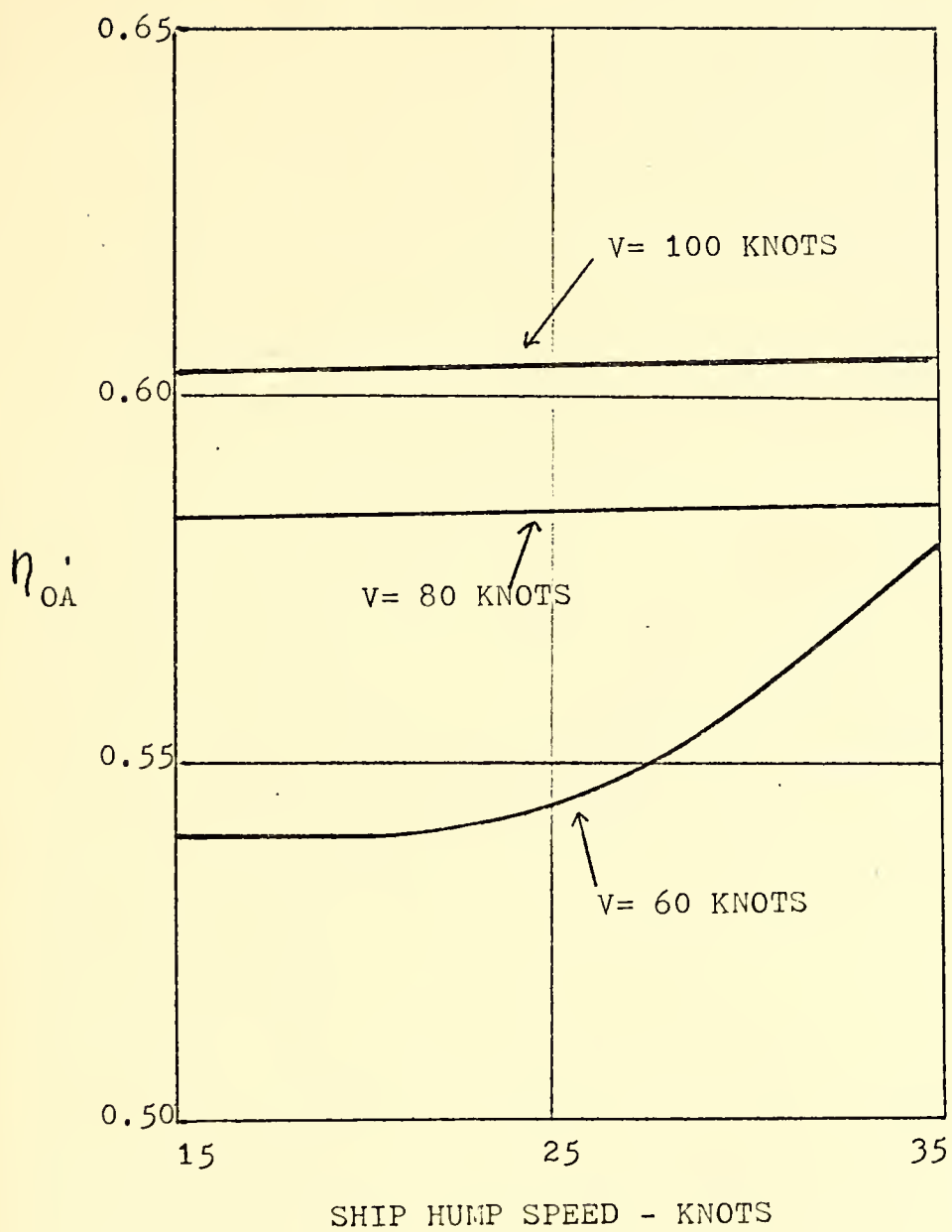


Figure 10 - DESIGN SPEED OVERALL INTERNAL EFFICIENCY  
FOR 2.5 ASPECT RATIO INLETS



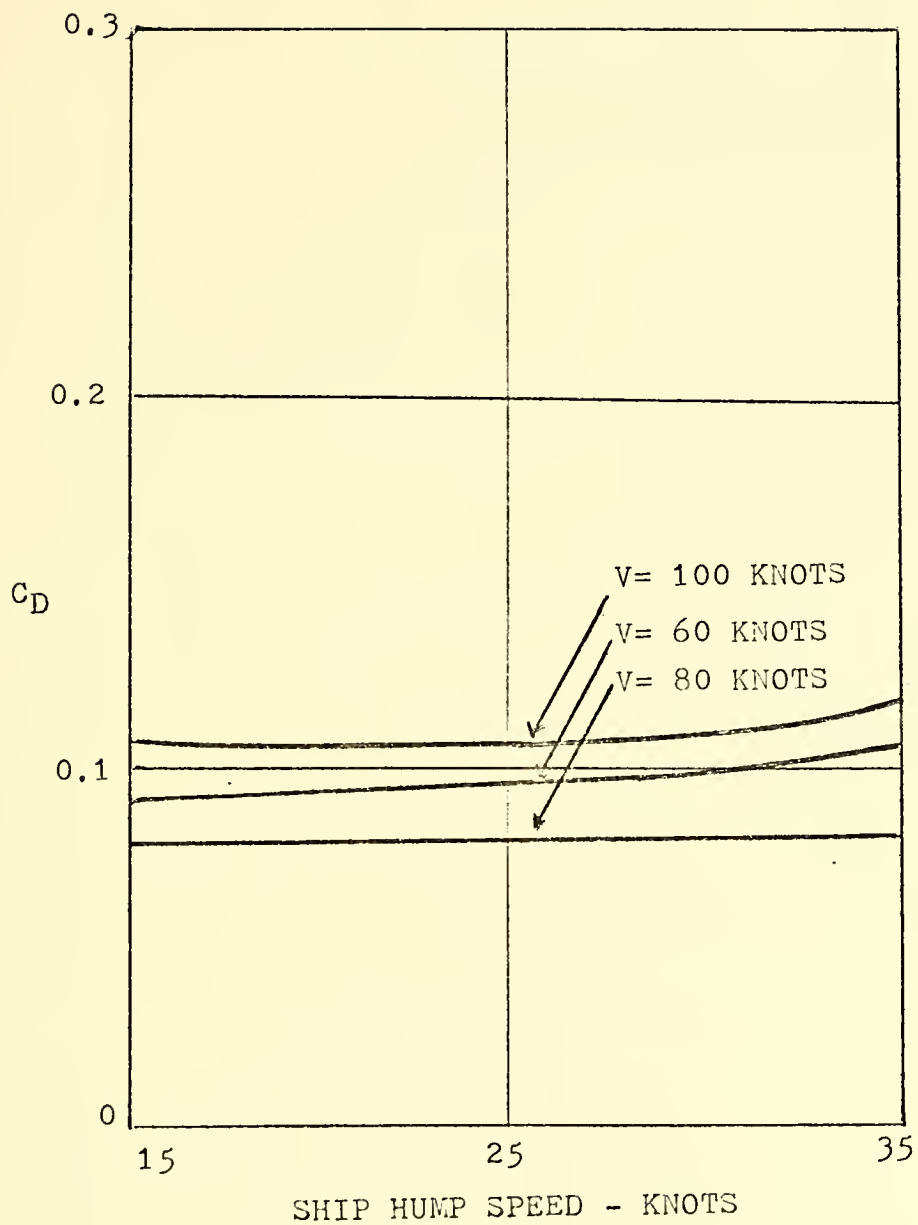
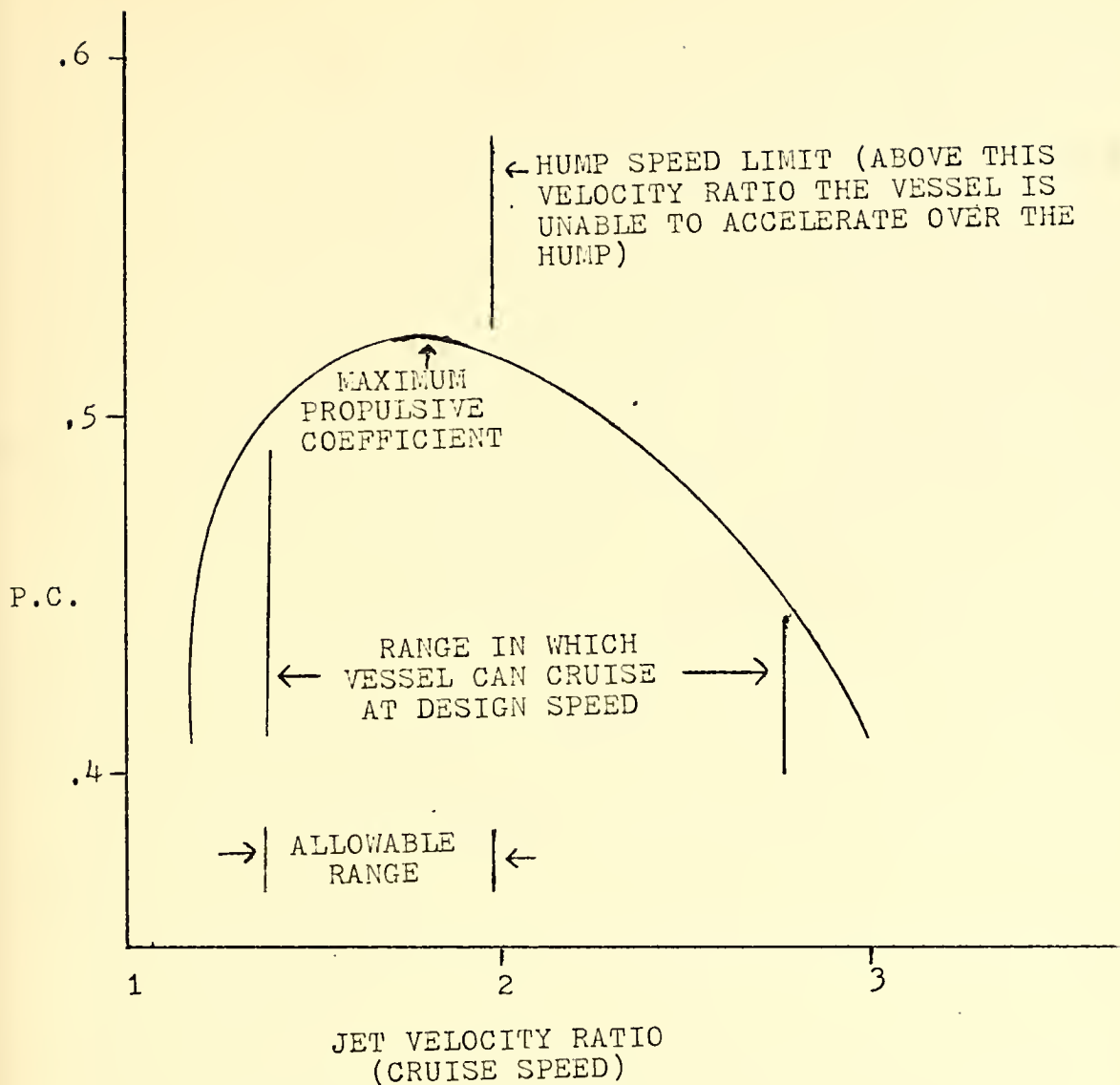


Figure 11 - INLET DRAG COEFFICIENT FOR 2.5 ASPECT RATIO INLETS







Drag = 230,000 lb. at 80 knots

Drag = 325,000 lb. at 30 knots

$\eta_{OA1} = .557$   $C = .984$

$\eta_{OA2} = .577$   $\eta_p = .915$

$C_D = .14$   $\eta_g = .98$

$C_A = 1.2$   $\eta_n = .98$

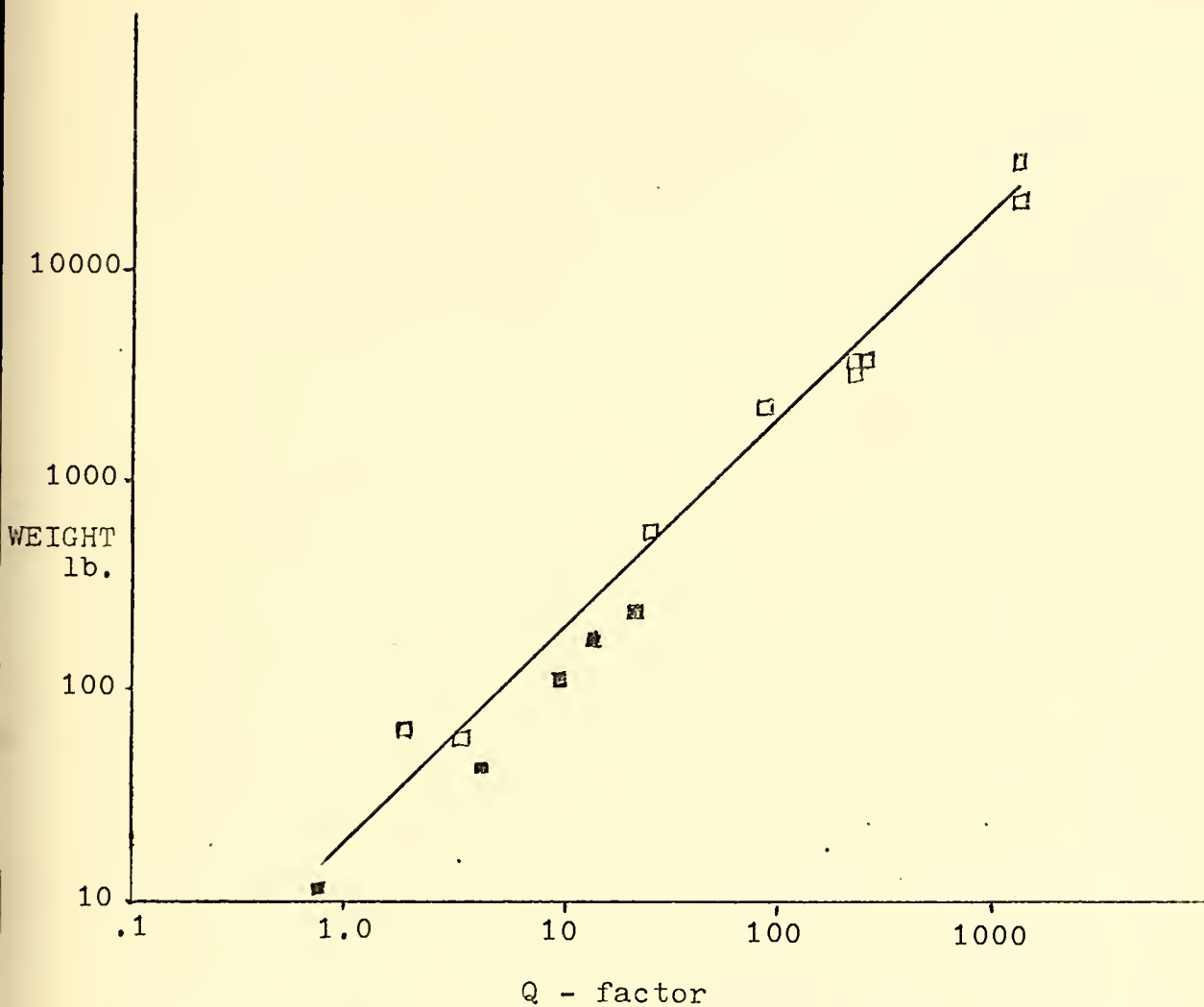
Engine normal horsepower = 22,200

Engine maximum horsepower = 22,500

Six engines

Figure 12 - VARIATIONS OF PROPULSIVE COEFFICIENT WITH JET VELOCITY RATIO





Open symbol: simple planetary gears  
 Closed symbol: compound gears  
 (Reference 2)

Figure 13 - CORRELATION OF DUDLEY'S METHOD OF ESTIMATING  
 REDUCTION GEAR WEIGHT



TABLE 1

COMPUTER PROGRAM OUTPUT

JET VELOCITY RATIO = 1.946

WEIGHTS

PUMPS DRY	=	29310.	ENGINES	=	63000.
PUMP WATER	=	6740.	FUEL	=	597913.
INLET SYSTEM	=	139254.	REDUCTION GEARS	=	14262.
TOTAL WEIGHT	=	850481.	ADDITIONAL WATER	=	0.

PUMP DATA

NUMBER OF STAGES	=	3	PUMP RPM-CRUISE	=	1177.
PUMP EFFICIENCY-CRUISE	=	91.14	PUMP EFFICIENCY-HUMP	=	91.13
S. SPEC. SPEED-CRUISE	=	6260.	N.P.S.H. - CRUISE	=	186.0
PUMP HEAD - CRUISE	=	921.7	PUMP HEAD - HUMP	=	1036.
PUMP INLET DIAMETER	=	2.849	PUMP LENGTH	=	5.784
FLOW COEFFICIENT-CRUISE	=	.1565	FLOW COEFFICIENT-HUMP	=	.1500
TIP VELOCITY-CRUISE	=	175.7	TIP VELOCITY-HUMP	=	182.0
PUMP FLOW-CRUISE	=	159.5	PUMP FLOW -HUMP	=	158.4
INLET DRAG - CRUISE	=	17764.	TOTAL RESIST.-CRUISE	=	247764
INLET AREA - CRUISE	=	4.332	INLET AREA-HUMP	=	11.51
INLET HEIGHT - CRUISE	=	1.038	INLET HEIGHT-HUMP	=	2.760
INLET WIDTH	=	4.171	INLET DIFFUSION RATIO	=	4.016
VARIABLE AREA FACTOR	=	2.657	REDUCTION GEAR RATIO	=	2.787



TABLE 2

COMPUTER OUTPUT FOR VARIOUS JET VELOCITY RATIOS

VELOCITY RATIO	WEIGHT RATIO	PROPULSIVE COEFFICIENT (OVERALL)	HORSEPOWER HUMP	HORSEPOWER CRUISE	PUMP RPM HUMP
1.6063	0.2306	0.4719	17586.8	20150.7	1007.7
1.6263	0.2260	0.4751	17837.6	20009.3	1021.8
1.6463	0.2219	0.4778	18088.3	19889.3	1035.7
1.6663	0.2182	0.4801	18338.8	19788.3	1049.3
1.6863	0.2147	0.4820	18589.1	19704.0	1062.7
1.7063	0.2116	0.4836	18839.3	19634.8	1075.8
1.7263	0.2087	0.4849	19089.3	19578.9	1088.8
1.7463	0.2072	0.4859	19339.2	19535.2	1101.5
1.7663	0.2048	0.4866	19588.9	19502.4	1114.1
1.7863	0.2025	0.4870	19838.3	19479.5	1126.4
1.8063	0.2005	0.4873	20087.6	19465.6	1138.7
1.8263	0.1985	0.4873	20336.7	19459.8	1150.7
1.8463	0.1968	0.4872	20585.7	19461.6	1162.6
1.8663	0.1952	0.4869	20834.5	19470.2	1174.3
1.8863	0.1937	0.4865	21083.1	19485.0	1185.9
1.9063	0.1923	0.4859	21331.6	19505.7	1197.4
1.9263	0.1910	0.4852	21579.9	19531.7	1208.7
1.9463	0.1898	0.4843	21828.1	19562.6	1219.9





## APPENDIX A

### ADDITIONAL INLET SYSTEM INFORMATION

Reference 1 is a report on calculated performance of flush inlet systems. It is a study of how various system parameters affect the inlet system's performance. The parameters studied include: the ship's hump speed and design speed, flow rate through the system, variable area factor, lip leading edge radius, aspect ratio, diffusion ratio, diffusion schedule, sidehull geometry, and the ratio of inlet width to fairing width.

The results of the study show that the most important factors affecting the inlet drag are the lip leading edge radius and the variable area factor. The leading edge must be sized to prevent cavitation and the onset of cavitation is determined by the velocity of the entering water. Since this velocity is in part controlled by the area of the inlet, the variable area factor and the lip leading edge radius are coupled. The inlet aspect ratio also affects the inlet drag, with smaller aspect ratio inlets having lower drag coefficients.

The internal efficiency is greatly affected by the diffuser schedule. The schedule used here is as follows:

First 20 percent of length	Diffusion = $6^{\circ}$
20 to 95 percent of length	Diffusion = $6^{\circ} + 12^{\circ} \times (p-20)/75$
95 to 100 percent of length	Diffusion = $18^{\circ} \times (100-p)/5$



Where  $p$  is the percent of total diffuser length measured from the inlet opening. The use of a smaller diffuser angle will result in higher efficiency but longer and heavier systems. The internal efficiency at hump speed increases with increasing hump speed.

The study covers cruise speeds between 60 and 100 knots and hump speeds between 15 and 35 knots. In general, the vessel's speed has very little influence on the system's drag and efficiency coefficients. The results of the study indicate that the performance coefficients of the system are only slightly affected by jet velocity ratio or by power levels. The power levels considered are between 1,000 and 40,000 horsepower.

It should be noted that the results are based on a minimum amount of data and apply to specific designs. They should be used only for designs similar to the one assumed here. Future data may widen the range of application.



### APPENDIX: B SAMPLE CALCULATION

The following sample calculation of the computer program is based on a ship having the following characteristics:

Resistance = 230,000 pounds at 80 knots

= 325,000 pounds at 30 knots

Displacement = 2000 ton      Range = 1000 miles

Diffuser outlet height = pump height = 6.5 feet.

Height of waterline = 2.0 feet.

Inlet aspect ratio is variable.

Six LM 2500 gas turbine engines are used.

The acceleration coefficient at hump is 1.2.

```

From Subroutine SESIN      CDIN1 = .1399
                           ETA1 = .57535
                           ETA2 = .69
                           CWIN = 4.9
                           C = .984

```

$$v_0(1) = (80) (1.689) = 135. \text{ ft/sec}$$
$$v_0(2) = 50.7 \text{ ft/sec}$$
$$\text{COR1} = (4.5)(2)(32.2)/(135)(135)(.984)(.984) = .0164$$

COR2 = .1128

$$\text{ETAOA}(1) = .5735 - .0164 = .5571$$
$$\text{ETAOA}(2) = .577$$

The portion of the program which compares the number of engines required uses the velocity ratio for maximum propulsive coefficient.

$$\text{FACT} = .984 + .1399/2 - .1399/(2) (135) = 1.053$$
$$V_{JVO} (1) = 1.053 + \sqrt{(1.053)(1.053) - (.984)(.984)(.557)}$$



VJVO(1) = 1.806. Which is the velocity ratio for maximum PRC.

Using an assumed pump efficiency of .9, PRC is:

$$\begin{aligned} \text{PRC} &= \frac{(1.73)(1.806 - .984 - .1399/2 + .1399/(2)(135))}{(1.806)(1.806) - (.984)(.5571)} \\ &= .487 \end{aligned}$$

The power required must be less than or equal to the available power. The required power is:

$$\begin{aligned} &(230,000)(135) + (.1399)(230,000)/(2(1.806 - .984 - .1399/2)) \\ &= 3.112 \times 10^7 \text{ ft-lb/sec.} \end{aligned}$$

The available power is:

$$(22,200)(.487)(550)(6) = 3.56 \times 10^7 \text{ ft-lb/sec.}$$

Therefore, six engines are sufficient to power the vessel at cruise speed. Having determined this, the program would subtract a designated amount from VJVO(1) and call subroutine PUMP. Since the least weight system in this example occurs at VJVO(1) = 1.946, this velocity ratio will be used for the sample calculation of subroutine PUMP.

$$\begin{aligned} Q(1) &= 230,000/(1.99)(135)(1.946 - .984 - .1399/2) \\ &= 958 \text{ ft}^3/\text{sec.} \end{aligned}$$

$$\text{AJET} = 958/(1.946)(135) = 3.655 \text{ ft}^2$$

$$\text{FACT} = .5 + 1.2(.1399)/4 = .54199$$

$$\begin{aligned} \text{VJVO}(2) &= .54199 + \sqrt{(.54199)^2 + \frac{1.2(320,000)}{1.99(3.655)(50.7)^2}} \\ &= 5.14 \end{aligned}$$

$$Q(2) = (3.655)(5.14)(50.7) = 950 \text{ ft}^3/\text{sec.}$$

$$\text{QQ}(1) = 958/6 = 159.5 \text{ ft}^3/\text{sec/pump}$$

$$\text{QQ}(2) = \quad \quad = 158.4 \text{ ft}^3/\text{sec/pump}$$





$$\begin{aligned} \text{HPP}(1) &= ((1.946)(1.946) - (.984)^2(.5571))(135)^2/64.4 \\ &= 921 \text{ ft.} \end{aligned}$$

$$\begin{aligned} \text{HPP}(2) &= ((5.14)(5.14) - .577)(50.7)^2/64.4 \\ &= 1.31 \text{ ft.} \end{aligned}$$

$$\text{HSV}(1) = 33. + (.984)^2(.5571)(135)^2/64.4 = 186 \text{ ft.}$$

$$\text{HSV}(2) = 33. + (.577)(50.7)^2/64.4 = 56.1 \text{ ft.}$$

$$\text{QX} = 159.5/158.4 = 1.007$$

$$\text{HX} = 921/1031 = 0.8933$$

Using VTIP = 182 ft/sec.

$$\text{RTIP} = 158.4/(3.1416)(182)(.15)(1. - .09) = 1.42 \text{ ft.}$$

$$\text{RPM}(2) = 182(60)/(1.42)(2)(3.1416) = 1220 \text{ rpm}$$

$$\text{SSS} = (1220)(158.4)^{.5}/(56.1)^{.75} = 749$$

\* note: This suction specific speed is 15,900 in the usual dimensions of  $\text{rpm}(\text{gal}/\text{min})^{.5}/\text{ft}^{.75}$  and below the 16,000 limit.

$$\text{SHI} = (32.2)(1031)/(182)^2 = 1.002. \text{ Therefore,}$$

$$\text{NSTG} = 3$$

$$\text{CA} = 1.0(.5)/1.0 = .5$$

$$\text{CB} = -1.0$$

$$\begin{aligned} \text{RX} &= -.5(1.007) + \sqrt{(1.007)^2((.5)^2 + 1.0) + .8933} \\ &= .9664 \end{aligned}$$

$$\begin{aligned} \text{ETAP}(2) &= 1.0 - ((3.666/(2)(1.42))^{.165}(1.0 - .915)) \\ &= .9113 \end{aligned}$$

$$\begin{aligned} \text{PRC}(2) &= 2.0(.98)^2(.9113)(5.14 - 1. - .1399(1.2)/2 \\ &\quad + .1399(1.2)/(2)(50.7))/((5.14)^2 - .577) \\ &= .2748 \end{aligned}$$



The required power at hump speed is:

$$(325,000)(50.7)(1.2) + \frac{(1.2)(.1399)(325,000)}{2(5.14 - 1. - 1.2(.1399)/2)}$$
$$= 1.97 \times 10^7 \text{ ft-lb/sec.}$$

The available power is:

$$(550)(.2748)(22,500)(6) = 2.04 \times 10^7 \text{ ft-lb/sec.}$$

Therefore, there is sufficient power to accelerate over the hump.

$$\text{ETAX} = -1.7(1.007)^2 + 3.42(1.007) - .72 = 1.0004$$

$$\text{ETAP}(1) = .9113(1.0004) = .9114$$

$$\text{PRC}(1) = \frac{2(.98)^2(.9114)(1.946 - .98 - .1399/2 + .1399/2(135))}{(1.946)(1.946) - .5571(.984)(.984)}$$
$$= .481$$

The power required at cruise speed is:

$$230,000(135) + .1399(230,000)/2(1.946 - .984 - .1399/2)$$
$$= 3.106 \times 10^7 \text{ ft-lb/sec.}$$

and the available power is:

$$(550)(.481)(22,200)(6) = 3.524 \times 10^7 \text{ ft-lb/sec.}$$

and the vessel has sufficient power to cruise at the design speed of 80 knots.

$$\text{RPM}(1) = (1220)(.96648) = 1179 \text{ rpm.}$$

$$\text{VTIP}(1) = 1179(2)(3.1416)(1.42)/60 = 175.3 \text{ ft/sec.}$$

Call subroutine WEIGHT. (NSTG = 3)

$$\text{XLP} = 2.03$$

$$\text{CW} = 439.5$$

$$\text{D1S} = 2.84 \text{ ft.}$$

The pump dry weight is:

$$\text{XWD} = (439.5)(2.84)^{2.3}(6) = 29,089 \text{ lb.}$$



$$PLP = (2.84)(2.03) = 5.76 \text{ ft.}$$

$$APUP = (.785)(2.84)^2(.91) = 5.76 \text{ ft}^2$$

The weight of the water in the pump is:

$$XWW = (0.523)(5.76)^2(1.99)(32.2)(6) = 6,671 \text{ lb.}$$

The weight of the inlet system is:

$$XWIN = (4.9)(958)^{1.5} = 139,000. \text{ lb.}$$

$$XWENG = 63,000. \text{ lb.}$$

$$GERAT = 3400/1220 = 2.78$$

$$SHP(1) = \frac{(1.99)(32.2)(958)(921.)}{550(6)(.9114)(.98)(.98)} = 19,573 \text{ hp/pump}$$

$$SHP(2) = \frac{(1.99)(32.2)(950)(1031)}{(550)(6)(.9113)(.98)(.98)} = 21,730 \text{ hp/pump}$$

The reduction gear q-factor is:

$$RQ = \frac{21,730 (3.78)^3}{3400 (2.78)} = 124.16$$

and the resulting reduction gear weight is:

$$XWGR = (9500)(124.16)(6)/(500) = 14,155 \text{ lb.}$$

$$SSS1 = (1179)(159.5)^{.5}/(186)^{.75} = 295.6$$

or, in standard units,  $SSS1 = 6,267.$

$$CAL = 230,000/(2000)(2240) = .051$$

$$VOTERM = 135. + 135(.1399)/2 = 144.5$$

$$ETERM = .554(135)^2/64.4 = 157.$$

$$SCONT = 1.99(32.2)(3.655)/550(.9114)(.98)^2 = .487$$

$$TI = 1000(1.689)/135(20) = .625 \text{ hr.}$$

$$VJ = 144.5/2 + \sqrt{144.5^2/4 + .051(2240)(2000)/1.99(3.655)}$$

$$= 262 \text{ ft/sec.}$$



$$\text{SHNG} = .487(262)((262)^2/64.4 - 157)/6 = 19,500 \text{ hp.}$$

$$\text{SFC} = .41/(19,500/22,200)^{.25} .423 \text{ lb/hp-hr}$$

$$\text{WT}(1) = .423(19,500)(.625)(6) = 31,050 \text{ lb.}$$

Which is the weight of fuel for the first time interval. The weight of fuel for the entire mission is:

$$\text{XWF} = 598,000 \text{ lb.}$$

$$\text{WTRAT} = \frac{(29089 + 6671 + 139000 + 63000 + 598000)}{2240(2000)}$$

$$= .189$$

$$\text{WTOT} = .189(2000)(2240) = 850,000. \text{ lb.}$$

Return to subroutine PUMP.

$$\text{PHI1} = 159.5(182)(.15)/175.3(158.4) = .156$$

$$\text{XDRAG} = .1399(1.99)(958)(135)/2 = 18,000 \text{ lb.}$$

$$\text{RESIST} = 230,000 + 18,000 = 248,000 \text{ lb.}$$

Return to main program.

$$\text{AINLET} = 958/135(.8)(2) = 4.33 \text{ ft}^2$$

$$\text{AD} = 5.76(6)/2 = 17.3 \text{ ft}^2$$

$$\text{DR} = 17.3/4.33 = 4.0$$

$$\text{VAF} = 950/50.7(.8)(4.33)(2) = 2.7$$

$$\text{AR} = \text{DR} = 4.0$$

$$\text{HIN} = \sqrt{4.33/4} = 1.04 \text{ ft}$$

$$\text{AIN2} = 2.7(4.33) = 11.7 \text{ ft}^2$$

$$\text{HIN2} = 2.7(1.04) = 2.8 \text{ ft}$$





## APPENDIX C

### COMPUTER PROGRAM DESCRIPTION AND USER'S GUIDE

The computer program consists of the main program and three subroutines. After reading in the data on the ship, engines, and inlet system as described below, the main program calls subroutine SESIN. This subroutine computes the inlet system's internal efficiencies at hump and cruise speeds and the inlet drag coefficient for the inlet specified. It returns these and "CU" which is the ratio of the entering water's momentum velocity to the vessel's speed.

The main program then computes the jet velocity ratio for maximum propulsive coefficient. Using the resulting velocity ratio and an assumed pump efficiency of .90 and nozzle and gear efficiencies of .98, the program computes the number of engines required.

Since the jet velocity ratio is the only system variable, the program is quite simple. The velocity ratio is varied in steps and subroutine PUMP is called. Subroutine PUMP returns the systems weight ratio and other data. The velocity ratio is increased until either the number of required pump stages exceeds three or the required power at either hump or cruise speeds exceeds the available power. The calculated data is then printed out and execution terminates.

Subroutine PUMP uses the equations developed in chapters 3 and 4 to find the required flow rates, pump heads, and net positive suction heads at cruise and hump speeds for the given



jet velocity ratio. It then designs the pump using these values and the tip velocity and suction specific speeds constraints. The pump is designed at hump speed to meet the stated criterion. The pump efficiency is determined by the pump diameter and a test is made to determine if sufficient power is available to accelerate over the hump. If there is sufficient power, the cruise speed performance is calculated, the pump is tested, and subroutine WEIGHT is called.

Subroutine WEIGHT uses the equations developed in chapter 4 to calculate the system weight. The exit angle of the diffuser is assumed to be 45 degrees and the transition pipe between the diffuser and the pump is assumed to be straight. The length of the pipe is then 1.414 times the difference in height between the diffuser and pump. The weight of the water in the pipe is calculated using this length. The user may wish to vary this angle and include other weights such as the weight of the pipe itself or a nozzle weight (XWPIP).

The user of the program must supply the following inputs to the program:

1. Engine performance data. The first twelve data cards in the program at present are engine data cards. (See "LIST OF PROGRAM VARIABLES, PERF (N,IENGH)", BELOW.)
2. A data card containing:  
IENGH - The type of engine to be used  
IAR - The type of inlet to be used  
NGT - The number of engines to be used (optional)
3. A data card containing:  
HE - The height of the diffuser exit above the inlet in feet



HEP - The height of the pump above the  
inlet in feet.  
HEW - The height of the outside waterline  
above the inlet in feet.  
CAC - The acceleration coefficient.

4. A data card containing:  
VO (1) - The ship's cruise speed in knots  
VO (2) - The ship's hump speed in knots  
DRAG (1) - The hull drag at cruise speed in pounds  
DRAG (2) - The hull drag at hump speed in pounds  
DISP - The ship's displacement in long tons  
RANGE - The range in nautical miles



## LIST OF PROGRAM VARIABLES

AD	- Diffuser outlet area	ft <sup>2</sup>
AINLET	- Inlet area at cruise speed	ft <sup>2</sup>
AIN2	- Inlet area at hump speed	ft <sup>2</sup>
AJET	- Jet area	ft <sup>2</sup>
APUP	- Pump inlet area	ft <sup>2</sup>
AR	- Inlet aspect ratio	
C	- $= (CU)^2$ The square of the ratio of the momentum velocity of entering water to the ship's velocity	
CAC	- Acceleration coefficient	
CAL	- Ratio of ship's drag to displacement	
CDIN1	- Inlet drag coefficient at cruise speed	
CDIN (I)	- Inlet drag coefficient	
COR1	- Correction factor for ETAOA (1)	
COR2	- Correction factor for ETAOA (2)	
CU	- Ratio of momentum velocity of inlet water to ship's velocity	
CW	- Pump weight coefficient	
CWIN	- Inlet system weight coefficient	
D1S	- Pump inlet diameter	
DCOF	- Inlet drag coefficient (subroutine weight)	
DEL	- Increment of change in jet velocity ratio	





DIS(1)	- Displacement after removing fuel	lb
DISP	- Displacement - entered in long tons converted to pounds	
DR	- Diffusion ratio	
DRAG (I)	- Ship's drag	lb
DRAT	- Ratio of pump's inlet hub radius to blade tip radius	
ENETA	- Overall internal efficiency times the square of the ratio of momentum velocity to ship velocity (used in subroutine weight)	
ETA1	- $\eta_{OA}$ at cruise speed	
ETA2	- $\eta_{OA}$ at hump speed	
ETAOA (I)	- $\eta_{OA}$	
ETAP (I)	- Pump efficiency	
ETAX	- Ratio of off design point pump efficiency to design point efficiency	
G	- Acceleration due to gravity	ft/sec <sup>2</sup>
GERAT	- Reduction gear ratio	
HA	- Atmospheric pressure head	ft
HE	- Height of diffuser outlet above baseline	ft
HEP	- Height of pump above baseline	ft
HEW	- Height of outside water-line above baseline	ft
HIN	- Inlet height (dimension) at cruise speed	ft



HIN2	- Inlet height (dimension) at hump speed	ft
HPP(I)	- Head across pump	ft
HSV(I)	- Net positive suction head	ft
HX	- Ratio of pump head at cruise to pump head at hump	
IAR	- Input to program = 1 for 2.5 aspect ratio inlets = 2 for varying aspect ratio inlets	
ICONT	- Program control	
IENGN	- Type of gas turbine = 1 - TF 35 = 2 - TF 40 = 3 - Proteus, 1500 RPM = 4 - Proteus, 1000 RPM = 5 - Tyne 1A = 6 - Tyne 1C = 7 - FT12 A = 8 - LM 1500 = 9 - LM 2500 =10 - FT4A-2C =11 - FT4A-12 =12 - FT4C-2	
IPRINT	- Output device number	
IREAD	- Input device number	
ISTEER	- Program control	
LAST	- Program control	
NGT	- Number of gas turbines	
NSTG	- Number of pump stages	
PC(L,M)	- Inducer stage characteristics	
PCA(L,M)	- Axial stages characteristics	
PC1MAX	- Maximum overall propulsive coefficient	
PC2MAX	- Maximum 'false' propulsive coefficient (ship's hull drag times cruise speed/550 SHP)	
PC1VJ	- Jet velocity ratio for PC1MAX	



PC2VJ	- Jet velocity ratio for PC2MAX	
PCOEF (J,K)	- Pump length and weight coefficients	
PERF (N,IENCN)	- Engine data where N is	
	1 - Normal SHP	HP
	2 - Maximum SHP	HP
	3 - SFC At normal SHP	$\frac{\text{lb}}{\text{HP} - \text{hr}}$
	4 - RPM	RPM
	5 - Weight of engine (dry)	lb
PHI	- Pump flow coefficient at hump speed	
PHI1	- Pump flow coefficient at cruise speed	
PI	- Constant = 3.1415927	
PLP	- Pump length	ft
PRC (I)	- Propulsive coefficient (overall)	
PRC1	- Propulsive coefficient (overall) main program	
PRNC1	- Propulsive coefficient (false) main program	
Q (I)	- Flow rate through system	$\text{ft}^3/\text{sec}$
QQ (I)	- Flow rate through each pump	$\text{ft}^3/\text{sec}/$ pump
QX	- Ratio of flow rate at cruise speed to flow rate at hump speed	
RANGE	- Ships Range	nautical miles
RESIST	- Total resistance of ship including inlet drag	lb
RHOW	- Density of water	$\frac{\text{slug} - \text{ft}^4}{\text{sec}^2}$



RPM (I)	- Pump RPM	RPM
RPM2	- Pump RPM at hump speed (subroutine SESIN)	RPM
RQ	- Reduction gear Q-factor	.
RTIP	- Pump inlet tip radius	ft
RX	- Ratio of pump RPM at cruise speed to RPM at hump speed	
SFC	- Specific fuel consumption	$\frac{\text{lb}}{\text{HP} \cdot \text{hr}}$
SHI	- Pump head coefficient	
SHNG	- Shaft horsepower required after fuel is removed	HP
SHP (I)	- Shaft horsepower	HP
SSS1,2	- Suction specific speed cruise speed and hump speed	
TI	- Time interval for fuel consumption calculation	hr
VAF	- Variable area factor (ratio of inlet area at hump speed to inlet area at cruise speed)	
VO(I)	- Ship velocity input and subroutine SESIN remainder of program	KTS ft/sec
VJ	- Jet velocity	ft/sec
VJVO(I)	- Jet velocity ratio	
VTIP(I)	- Pump blade tip velocity	ft/sec
WIDTH	- Width of inlet opening	ft
WT(K)	- Weight of fuel required for one time period	lb
WTMIN	- Minimum weight ratio	
WTOT	- Total system weight	lb
WTRAT	- Weight ratio	





WVJ	- Jet velocity ratio for minimum weight ratio	lb
XDRAG	- Inlet system drag	
XKEEP	- Minimum weight ratio (subroutine pump)	
XK	- Reduction gear K - factor	
XN	- Factor for SFC versus power curve	
XNGT	- Number of gas turbines	
XWD	- Pump dry weights	lb
XWENG	- Weight of engines	lb
XWF	- Total fuel weight	lb
XWGR	- Reduction gear weight	lb
XWIN	- Inlet system weight	lb
XWPIP	- Transition pipe weight (user may add additional weights)	lb
XWW	- Pump water weight	lb
XX(J,K)	- Main program outputs where	
	1 - Jet velocity ratio	
	2 - Weight ratio	
	3 - Overall propulsive coefficient	
	4 - False propulsive coefficient	
	5 - Shaft horsepower at hump speed	HP
	6 - Shaft horsepower at cruise speed	HP
	7 - Suction specific speed at hump speed	
	8 - Pump RPM at hump speed	RPM



9 - Number of pump stages

XLP

- Pump length coefficient

\*Note A. As used above (I) indicates ship's speed.

I = 1 - Cruise speed

= 2 - Hump speed



```

C SURFACE EFFECT SHIP FLUSH INLET WATERJET SYSTEM
COMMON/FCUT/PRC1,SSS2,RPW2
COMMON/INDEX/IAR,IPRINT,IREAD,IENGN,ASTG,LAST
COMMON/PARIN/ETA1,ETA2,CU,CDINI
COMMON CKIN
COMMON/HEAD/HA,HEW,HEP,C(2),HE
COMMON/PERFQ/PERF(5,12),WTRAT,XNGT
COMMON/CONST/PI,G,RHCK,XK
COMMON/PCWA/CAC,CJP1,CCR2
COMMON/SHIP/DISP,RANGE,IRAG(2)
COMMON/WEMA/APUP,GERAT,SHF(2)
DIMENSION ETADA(2),CDIN(2),XX(2C,9),PRC(2)
IREAD=8
IPRINT=5
CC 2 J=1,12
READ(IREAD,1003)(PERF(I,J),I=1,5)
1003 FORMAT(5F10.3)
2 CONTINUE
READ(IREAD,1001) IENGN,IAR,NGT
1001 FORMAT(3I5)
READ(IREAD,1002) HE,HEP,HEW,CAC
1002 FORMAT(4F10.2)
READ(IREAD,1000) VG(1),VG(2),DRAG(1),DRAG(2),DISP,RANGE
1000 FORMAT(6F10.1)
WRITE(IPRINT,5000) DISP,DRAG(1),VG(1),DRAG(2),VC(2)
5000 FORMAT(1H1,20X,'THIS RUN IS FOR A ',F7.1,' TON SES WHOSE DRAG IS ',
1,F9.1,' POUNDS AT ',F6.1,' KNOTS',/21X,'AND ',F9.1,' POUNDS AT A HU
2MP SPEED OF ',F5.1,' KNOTS',/)
DISP=DISP*2240.
PI=3.1415927
PA=33.0
G=32.174
RHCK=1.99
XK=500.
CALL SESIN
C CONVERT VELOCITIES TO FEET/SECOND

```



```

CC 3 I=1,2
VC(1)=VC(1)*1.689
3 CONTINUE
CUR1=(PE-HEP)*2.*G/(VC(1)*VO(1)*CU*CU)
CCR2=(PE-HEP)*2.*G/(VC(2)*VO(2))
C COMPUT NGT REQUIRED ASSUMING VJVO=1.8 AND THE PRODUCT
C OF THE NOZZLE, GEAR, AND PUMP EFFICIENCIES = .865
ETACA(1)=ETAL-CCRI
CCIN(1)=CCIN1
FACT=CU*CCIN(1)/2.-CCIN(1)/(2.*VO(1))
VJVO(1)=FACT*SQRT(FACT*FACT-CU*CU*ETACA(1)+2.*G*(PEP-HE)/(VO(1)*
1VG(1)))
PRC(1)=1.73*(VJVC(1)-CU-CCIN(1)/2.+CCIN(1)/(2.*VO(1)))/(VJVC(1)*
1VJVO(1)-CU-CU*ETACA(1)+2.*G*(PEP-HE)/(VC(1)*VC(1)))
IF(NGT.GT.0) GO TO 40
NGT=2
40 NGT=FLCAT(NGT)
IF(DRAG(1)*VU(1)+CCIN(1)*DRAG(1)/(2.*(VJVC(1)-CU-CCIN(1)/2.))-LE.
1PERF(1,1ENG)*PRC(1)*XNGT*550.) GO TO 45
NGT=NGT+2
GC TO 40
45 CONTINUE
WRITE(IPRINT,5001)NGT
5001 FORMAT(5X,'NUMBER OF ENGINES=',I3//)
I=C
IJ=C
PC2MAX=C.C
PC1MAX=C.C
WTMIN=1.C
DEL=C.02
VJVC(1)=VJVO(1)-10.*DEL
50 CONTINUE
CALL PUMP
IJ=IJ+1
IF(IJ.GT.35) GO TO 42
GC TO 43

```





```

42 IF(I.EQ.C) GC TO 78
43 CONTINUE
   PRNC1=DRAG(1)*VG(1)/(XNG1*STP(1)*550.)
   IF(WTRAT.GE.1.0) GO TC 57
   IF(WTMIN.LE.WTRAT)GO TO 51
   WTMIN=WTRAT
   WVJ=VJVC(1)
51 CONTINUE
   IF(PC1MAX.GT.PRC1) GC TC 52
   PC1MAX=PRC1
   PC1VJ=VJVC(1)
52 CONTINUE
   IF(PC2MAX.GT.PRNC1) GO TO 53
   PC2MAX=PRNC1
   PC2VJ=VJVC(1)
53 CONTINUE
   GC TO 54
57 CONTINUE
   IF(I.GT.C) GC TC 60
   VJVC(1)=VJVC(1)+DEL
   GC TC 50
54 I=I+1
   IF(I.GT.20) GO TO 60
   XX(I,1)=VJVC(1)
   XX(I,2)=WTRAT
   XX(I,3)=PRC1
   XX(I,4)=PRNC1
   XX(I,5)=STP(2)
   XX(I,6)=STP(1)
   XX(I,7)=SSS2*21.2
   XX(I,8)=RPM2
   XX(I,9)=FLOAT(NSTG)
   VJVC(1)=VJVC(1)+DEL
   GC TO 50
60 CONTINUE
   AINLET=Q(1)/(VG(1)*.8*2.)

```



```

AC=APUP*XNGT/2.
CR=AC/AINLET
VAF=0(2)/(VC(2)*.8*AINLET*2.)
IF(IAK.EQ.2) GO TO 75
AR=2.5
74 CONTINUE
FIN=SQRT(AINLET/AR)
WIDTH=AR*FIN
GC TC 74
75 AR=CR
GC TC 74
76 CONTINUE
AIN2=VAF*AINLET
HIN2=VAF*FIN
WRITE(IPRINT,4100) AINLET,AIN2,HIN,HIN2,WIDTH,DR,VAF,GERAT
4100 FORMAT(5X,'INLET AREA-CRUISE *****',F10.4,10X,'INLET AREA-H
      LUMP *****',F10.4/5X,'INLET HEIGHT-CRUISE *****',F10
      2.4,10X,'INLET HEIGHT-HUMP *****',F10.4/5X,'INLET WIDTH ***
      3 *****',F10.4,10X,'INLET DIFFUSION RATIO *****',F10.4
      4/5X,'VARIABLE AREA FACTOR *****',F10.4,10X,'REDUCTION GEAR RAT
      5IC *****',F10.4/)//)
WRITE(IPRINT,4200) PC1MAX,PC1VJ,PC2MAX,PC2VJ,WTMIN,WVJ
4200 FORMAT(5X,'MAXIMUM OVERALL PROPULSIVE COEFFICIENT=',F10.6,' AT VJV
      1C=',F10.4/6X,'MAXIMUM FALSE PROPULSIVE COEFFICIENT=',F10.6,' AT V
      2JVC=',F10.4/17X,'MINIMUM TOTAL WEIGHT RATIO=',F10.6,' AT VJVC=',F1
      30.4)
WRITE(IPRINT,4300)
4300 FORMAT(1H1,' VELOCITY WEIGHT PROPULSIVE PROCPULSIVE
      1FCRSEPOWER HORSEPOWER SUCTION PUMP NUMBER')
WRITE(IPRINT,4310)
4310 FORMAT(4X,'RATIO',6X,'RATIO',4X,'COEFFICIENT',4X,'COEFFICIENT',7X,
      1'HUMP',9X,'CRUISE',6X,'SPECIFIC',5X,'RPM',7X,'GF',/25X,'(OVERALL)',
      26X,'(FALSE)',35X,'SPEED',7X,'HUMP STAGES'//)
WRITE(IPRINT,4400)((XX(L,K),K=1,9),L=1,1)
4400 FORMAT(/ / 20(4X,F6.4,4X,F6.4,7X,F6.4,9X,F7.1,7X,F7.1,5X,
      1F7.1,4X,F6.1,5X,F3.1/))

```



```
WRITE(IPRINT,4500)  
4500 FORMAT(1F1)  
78 CONTINUE  
STOP  
END
```



```

SUBROUTINE SESIN
COMMON/PARIN/ETA1,ETA2,CU,CDINI
COMMON/INDEX/IAR,IPRINT,IREAD,IENGN,NSTG,LAST
COMMON/VELOC/VJ(2),VJVC(2)
COMMON CAIN
C CALCULATION CF OVERALL INTERNAL EFFICIENCY FOR 2.5 ASPECT
C RATIO INLETS
IF (IAR.EQ.2) GO TO 30
F=.602
E=.584
C=.00015*VO(2)*VO(2)-.0056*VO(2)+.59025
A=(C+F-2.*E)/800.
B=(E-F)/20.-140./800.*(C-2.*E+F)
C=10.*F-15.*E+6.*D
ETA1=A*VC(1)+VO(1)+B*VC(1)+C
CU=.537
D=.76-(VC(2)-15.)*.004
F=.735-(VC(2)-15.)*.005
E=.745-(VC(2)-15.)*.005
A=(C+F-2.*E)/800.
B=(E-F)/20.-140./800.*(C+F-2.*E)
C=10.*F-15.*E+6.*D
ETA2=A*VC(1)+VJ(1)+B*VC(1)+C
C CALCULATION CF INLET DRAG COEFFICIENT FOR 2.5 ASPECT
C RATIO INLETS
F=.11
E=.0006*VC(2)+.084
C=.092
A=(C+F-2.*E)/800.
B=(E-F)/20.-140./800.*(C-2.*E+F)
C=10.*F-15.*E+6.*D
CCINI=A*VO(1)*VO(1)+B*VC(1)+C
CAIN=.6.C
RETURN
30 CCNTINUE
D=.000225*VO(2)*VO(2)-.0085*VO(2)+.611875

```





```

F=.00006*VC(2)*VC(2)-.0022*VC(2)+.5855
F=.594
A=(C+F-2.*E)/800.
B=(E-F)/20.-140./800.*(C+F-2.*E)
C=10.*F-15.*E+6.*D
ETA1=A*VC(1)*VO(1)+B*VC(1)+C
ETA2=.75-.004*(VO(2)-15.)
F=.133
D=.000065*VO(2)*VO(2)-.0022*VO(2)+.120375
F=.215
A=(C+F-2.*E)/800.
B=(E-F)/20.-140./800.*(E+F-2.*E)
C=10.*F-15.*E+6.*D
CDIA1=A*VC(1)*VC(1)+B*VC(1)+C
CWIN=4.7
CU=.984
RETURN
END

```



```

SUBROUTINE PUMP
COMMON/PCUT/PRC1,SSS2,RPM2
COMMON/INDEX/IAR,IPRINT,IREF,IENGN,NSTG,LAST
COMMON/PARIN/ETA1,ETA2,CU,CCIN1
COMMON/VELCC/VO(2),VJVO(2)
COMMON/FUMA/CAC,COR1,CCR2
COMMON/SHIP/DISP,RANGE,DRAG(2)
COMMON/CCCF/CCCF,ENETA,AJET
COMMON/HEAD/FA,HEW,HFP,G(2),HE
COMMON/PLA /RIP,RPN(2),ETAP(2),DRAT,HSV(2),HFP(2)
COMMON/PERFO/PERF(5,12),WTRAT,XNGT
COMMON/CCNST/PI,G,RHCB,XK
DIMENSION Q(2),ETAUA(2),CDIN(2),PC(2,3),PCA(2,3),VTIP(2),PRC(2)
DATA PC/-3.0,-1.7,4.8,3.42,-0.6,-0.72/
DATA PCA/-1.0,-1.7,1.0,3.42,1.0,-0.72/
ETAP(1)=0.0
ETAP(2)=0.0
CORRECT OVERALL INTERNAL EFFICIENCY AND DRAG COEFFICIENT
FOR EFFECTS OF HEIGHT
ETAUA(1)=ETA1-CCR1
ETAUA(2)=ETA2-COR2
CCIN(1)=CCIN1
CDIN(2)=CCIN(1)
ENETA=ETACA(1)*CU*CU
CCCF=CCIN(1)
C COMPUTE REQUIRED FLOW AND HEAD AND NPSH AT TAKEOFF(2)
C AND CRUISE(1)
G(1)=Q*G(1)/(RHO*VO(1)*(VJVO(1)-CU-CDIN(1)/2.))
AJET=Q(1)/(VJVO(1)*VO(1))
FACT=.5+CAC*CCIN(2)/4.
VJVO(2)=FACT+SQRT(FACT*FACT+CAC*DRAG(2)/(RHO*AJET*VO(2)*VC(2)))
Q(2)=AJET+VJVO(2)*VO(2)
C=CU*CU
DO 2 I=1,2
IF(1.EC.2) C=1.0
G(1)=G(1)/XNGT

```



```

HPP(1)=HEP-HE+((VJVO(1)*VJVO(1)-C*ETAQA(1))*VC(1)*VO(1))/(2.*G)
FSV(1)=FA-HEP+HE+(C*ETACA(1)*VO(1)*VO(1))/(2.*G)
2  CONTINUE
LAST=1
CRAT=.3
PHI=C.15
GX=CC(1)/CQ(2)
HX=HPP(1)/HPP(2)
VTIP(2)=2C0.
XKEFF=1C.
ISTEER=G
ICNT=C
40  CONTINUE
RTIP=SQRT(CQ(2)/(PI*VTIP(2)*PHI*(1.-DRAT*CRAT)))
RPM(2)=VTIP(2)*6C./((RTIP*2.*PI)
SSS=KPM(2)*CC(2)**.5/FSV(2)**.75
IF(ISTEER.GT.0) GO TC 51
IF(SSS.LT.755.) GO TC 5C
VTIP(2)=VTIP(2)-1.
CC TC 4C
50  CONTINUE
ISTEER=1C
51  CONTINUE
SHI=G*HPP(2)/(VTIP(2)*VTIP(2))
IF(SHI.GT.1.C1) GO TC 36
52  NSTG=2
IF(SHI.LE.0.41) NSTG=1
IF(SHI.GT.C.71) NSTG=3
IF(NSTG-2)60,70,70
60  IF(ICNT-10)61,65,61
61  ICNT=1C
CA= PC(1,2)/PC(1,3)*.5
CE=PC(1,1)/PC(1,3)
RX=-CA*GX-SQRT(QX*OX*(CA*CA-CR)+HX/PC(1,3))
65  CONTINUE
ETAP(2)=1.0-((3.666/(2.*RTIP))**.165*(1.-.915))

```



```

PRC(2)=2.0*.58*.98*ETAP(2)*(VJVO(2)-1.-CDIN(2)*CAC/2.+CDIN(2)*CAC/
1(2.*VO(2)))/(VJVO(2)*VJVO(2)-ETAGA(2)+2.*(HEP-HE)*G/(VO(2)*VO(2)))
IF(ORAG(2)*VC(2)*CAC+CAC*CCIN(2)*CRAG(2)/(2.*(VJVO(2)-1.-CAC*CCIN(
12)/2.)).LE.550.*PPC(2)*PERF(2,IENG)*XNGT) GC TC 75
VTIP(2)=VTIP(2)-1.
GC TO 4C
75 CCNTINUE
IF(ICONT.GT.11) GO TC 76
ETAX=PC(2,1)*QX**2+PC(2,2)*QX+PC(2,3)
IF(ETAX.LE.0.) ETAX=.001
ETAP(1)=ETAP(2)*ETAX
77 CCNTINUE
PRC(1)=2.*.98*.98*ETAP(1)*(VJVO(1)-CU-CDIN(1)/2.+CDIN(1)/(2.*VO(1)
1))/(VJVO(1)*VJVO(1)-C*ETACA(1)+2.*C*(HEP-HE)/(VC(1)*VO(1)))
IF(CRAC(1)*VO(1)+CDIN(1)*ORAG(1)/(2.*(VJVO(1)-CU-CDIN(1)/2.)).LE.
1PERF(1,IENG)*PRC(1)*XNCT*550.) GC TC 78
VTIP(2)=VTIP(2)-1.
GC TC 4C
7C CCNTINUE
IF(ICONT.CT.11) GO TC 65
ICONT=2C
CA=PCA(1,2)/PCA(1,3)*.5
CB=PCA(1,1)/PCA(1,3)
RX=-CA*QX+SCRT(QX*QX*(CA*CA-CB)+HX/PCA(1,3))*(CA/ABS(CA))
GC TO 65
36 IF(LAST-2) 9C,80,52
76 CCNTINUE
ETAX=PCA(2,1)*QX**2+PCA(2,2)*QX+PCA(2,3)
IF(ETAX.LE.0.) ETAX=.001
ETAP(1)=ETAP(2)*ETAX
GC TC 77
78 CCNTINUE
RPM(1)=RPM(2)*RX
VTIP(1)=RPM(1)*2.*PI*RTIP/60.
IF(VTIP(1).LE.20C.) GC TC 3C
VTIP(2)=VTIP(2)-1.0

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GC TC 40
3C CCNTINUE
CALL WEIGHT
IF(LAST.EQ.3) GC TC 83
IF(XKEEP.LT.WTRAT) GC TC 80
XKEEP=WTRAT
LAST=2
VTIP(2)=VTIP(2)-1.
GC TC 4C
8C CCNTINUE
LAST=3
VTIP(2)=VTIP(2)+1.0
GC TC 40
83 CCNTINUE
GC TC 55
90 WRITE(IPRINT, 2012) VJVC(1),ETAP(2),ETAP(1)
2012 FORMAT(5X,'THERE IS NO SOLUTION AT VJVC(1)=' ,3(F15.8)//////)
WTRAT=1.0
RETURN
95 CCNTINUE
SSS2=SSS
PRC1=PRC(1)
PHI1=QQ(1)*VTIP(2)*PHI/(VTIP(1)*QQ(2))
PHI2=RFV(2)
XCRAG=CCIN(1)*RHON*Q(1)*VO(1)/2.
RESIST=CRAG(1)+XCRAG
WRITE(IPRINT,3100)PHI1,PHI,VTIP(1),VTIP(2),QQ(1),QQ(2)
3100 FORMAT(5X,'FLOW COEFFICIENT-CRUISE *****',F10.4,10X,
1,'FLOW COEFFICIENT-HUMP *****',F10.4/5X,'TIP VELOCITY-CRUISE ***
2*****',F10.2,10X,'TIP VELOCITY-HUMP *****',F10.2/5X,
3,'PUMP FLOW-CRUISE *****',F10.2,10X,'PUMP FLOW-HUMP *****
4*****',F10.2/)//)
WRITE(IPRINT,3111) XCRAG,RESIST
3111 FORMAT(5X,'INLET DRAG-CRUISE *****',F10.1,10X,'TOTAL RESIST
ANCE-CRUISE *****',F10.1/)//)
RETURN

```



```

SUBROUTINE WEIGHT
COMMON/INDEX/IAR,IPRINT,IREAD,IENG,NSTG,LAST
COMMON/VELCC/VO(2),VJVC(2)
COMMON/CCCF/CCCF,ENETA,AJET
COMMON CWIN
COMMON/SHIP/DISP,RANGE,CRAG(2)
COMMON/HEAD/HA,HEW,HEF,C(2),HE
COMMON/FUM /RTIP,RPM(2),ETAP(2),DRAT,HSV(2),HPP(2)
COMMON/PERFC/PERF(5,12),WTRAT,XNGT
COMMON/CCNST/PI,G,RHCK,XK
COMMON/WEWA/APUP,GERAT,SFP(2)
DIMENSION PCCEF(3,2),WT(21),DIS(21)
DATA PCCEF/ 1.71,1.75,2.C3,347.C,393.5,439.5/
40 XLP=PCCEF(NSTG,1)
CW=CCCF(NSTG,2)
DIS=2.*RTIP
XW=CW*DIS**2.3*XNGT
FLP=DIS**XLP
APUP=.785*DIS**2.*(1.-DRAT*DRAT)
XW=.523*APUP*PLP*RHCK*G*XNGT
XWIN=CWIN*Q(1)**1.5
XWPIP=FFCW*G*(HEP-HE)*APUP*XNGT/.7C7
XWENG=PERF(5,IENG)*XNGT
GERAT=PERF(4,IENG)/RPM(2)
CC 2 I=1,2
2 SHP(1)=RHCK*G*Q(1)*HPP(1)/(550.*XNGT*ETAP(1)**.98*.93)
RG=SHP(2)/PERF(4,IENG)*(GERAT+1.)**3./GERAT
XWGR=.5CC.*RC/XK*XNGT
SSS1=RPM(1)*(Q(1)/XNGT)**.5/HSV(1)**.75
SSS1=21.2*SSS1
CAL=CRAG(1)/DISP
XWF=0.0
WT(1)=0.C
VTERM=VC(1)+VO(1)*DCCF/2.
ETERM=ENETA*VO(1)*VO(1)/(2.*G)-HEP+HE
CIS(1)=DISP

```



```

SCONT= RHO*G*AJET/(550.*ETAP(1)*.98*.98)
N=21
TI=RANCE*1.689/(VC(1)*2C.)
CC 1 I=2,N
DIS(I)=DIS(I-1)-WT(I-1)
VJ=VCTEFM/2.+SQRT(VCTERM*VOTERM/4.+CAL*DIS(I)/(RHO*AJET))
SHNG=SCCN1*VJ*(VJ*VJ/(2.*G)-ETERM)/XNGT
XA=C.25
IF (SHNG.L1.C.7*PERF(1,IENGN)) XA=0.75
SFC=PERF(3,IENGN)/((SHNG/PERF(1,IENGN))*XN)
WT(I)=SFC*SHNG*TI*XNGT
XWF=WT(I)+XWF
1 CCNTINUE
WKAT=(XWC+XWW+XWIN+XWPIP+XWENG+XWGR+XWF)/DISP
WTOT=WKAT*DISP
IF (WKAT.GT.1.0) GC TC 7
IF (LAST.EC.3) GC TC 4
RETURN
4 CCNTINUE
ETAP(1)=ETAP(1)*100.
ETAP(2)=ETAP(2)*100.
WRITE(IPRINT,2100) VJVC(1)
2100 FORMAT(3CX,'***** SYSTEM WEIGHTS AT VELOCITY RATIO ='F6.3,
1' *****')
WRITE(IPRINT,2200) XWC,XWENG,XWGR,XWIN
2200 FORMAT(/ 14X,'PUMP DRY ='F10.2,' ENGINE ='F10.2,' REDU
1CTION GEAR ='F10.2,' INLET SYSTEM ='F10.2)
WRITE(IPRINT,2300) XWW,XWF,XWPIP
2300 FORMAT(13X,'PUMP WATER ='F10.2,' FUEL ='F10.2,
1' ADDITIONAL WATER ='F10.2)
WRITE(IPRINT,2400) WTC
2400 FORMAT(5X,'TOTAL SYSTEM WEIGHT='F10.2///)
WRITE(IPRINT,2500)
2500 FORMAT(46X,'FLMP DATA')
WRITE(IPRINT,2600) NSTG,RPM(1),ETAP(1),ETAP(2),SSS1,HSV(1)
2600 FORMAT(5X,'NUMBER OF STAGES *****',I10,10X,

```



```

1 PUMP RPM-CRUISE ****='F10.2/5X,'PUMP EFFICIENCY-CRUISE
2 ****='F10.4,10X,'PUMP EFFICIENCY-HUMP ****='F10.4/5X,
3 SUCTION SPEC. SPEED-CRUISE **='F10.2,10X,'N. POS. SUCT. HEAD-CRUISE
4 **='F10.2)
    WRITE(IPRINT,2610) HPP(1),HPP(2),DIS,PLP
2610 FORMAT(5X,'PUMP HEAD-CRUISE ****='F10.2,10X,
1 PUMP HEAD-HUMP ****='F10.2/5X,'PUMP INLET DIAMETER ***
2 ****='F10.4,10X,'PUMP LENGTH ****='F10.4)
    RETURN
7 WTRAT=1.C
    LAST=3
    WRITE(IPRINT,2010) VJVC(1),WTOT
2010 FORMAT(5X,'SYSTEM TOO HEAVY VJVO=',F5.3,5X 'WEIGHT=',F10.1)
    RETURN
    END

```





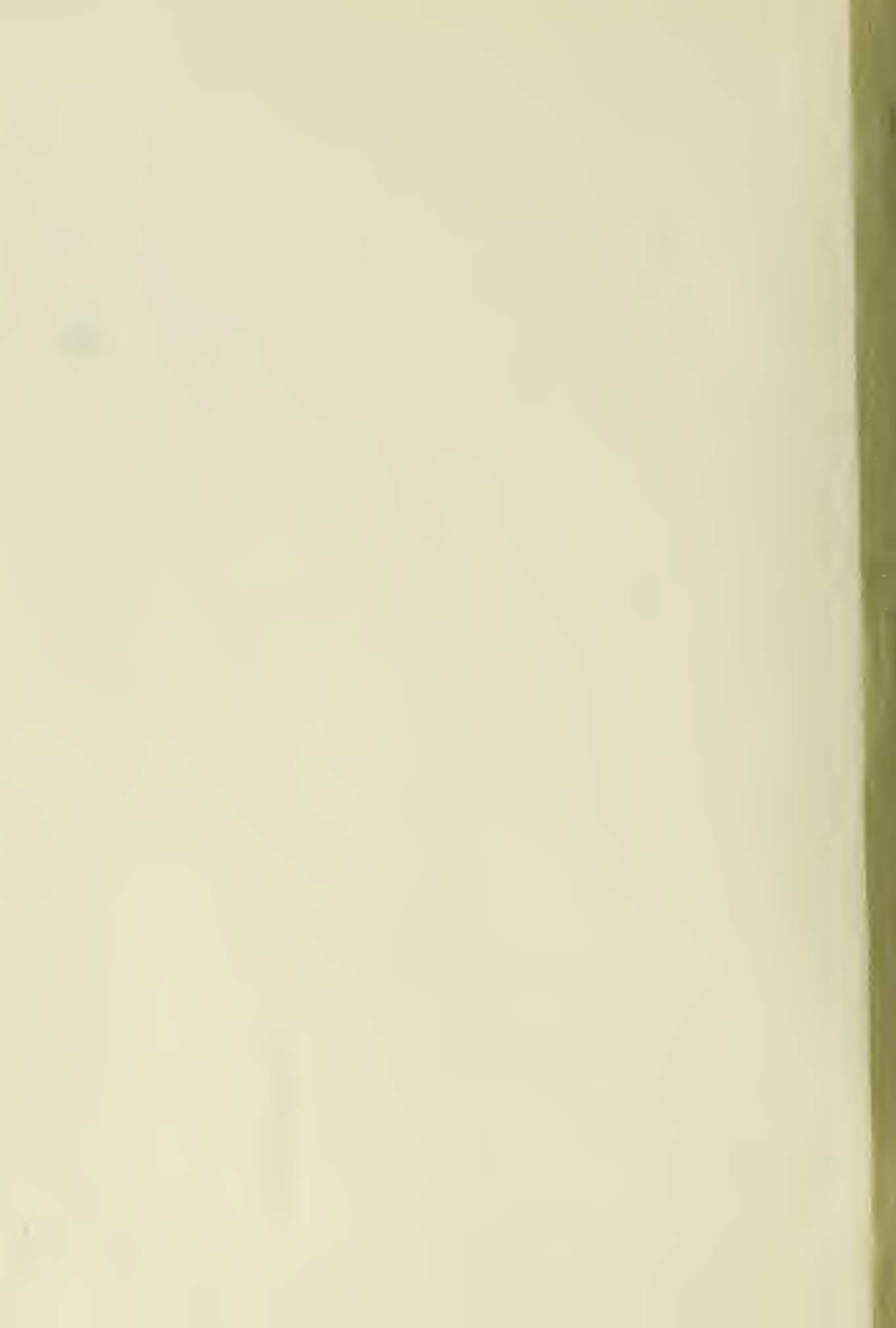
C SAMPLE INPUT  
C ENGINE DATA

222C.	284C.	.59	1450C.	1050.
285C.	306C.	.55	1450C.	1050.
280C.	351C.	.63	1500.	3200.
280C.	351C.	.63	1000.	3330.
332C.	425C.	.49	3110.	2800.
410C.	530C.	.47	3110.	2800.
222C.	234C.	.79	9000.	1010.
1250C.	1400C.	.575	5500.	7500.
2220C.	2250C.	.41	3400.	10500.
1915C.	2420C.	.52	3600.	14200.
2175C.	2695C.	.52	3000.	14200.
2760C.	3440C.	.48	3600.	14200.

C ENGINE TYPE AND INLET TYPE

5 2 6 SYSTEM HEIGHTS AND ACCELERATION COEFFICIENT

6.5	6.5	2.0	1.2
80.	30.	23000C.	32500C.
		2000.	1000.



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